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EROSION-CORROSION OF BRUCE "A" BLOWDOWN LINES DURING CHEMICAL CLEANING

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ABSTRACT

Flow-through chemical cleaning was performed on models of Bruce "A" steam-generator blowdown lines to determine if erosion-corrosion could occur. Uninhibited iron removal solvent promoted massive erosion-corrosion on carbon steel elbows, welds and shell material. Iron removal solvent containing CCI-801 inhibitor did not promote gross erosion-corrosion although the carbon steel corrosion rate was greater than predicted by static tests and showed some dependence on inhibitor concentration. The copper removal solvent and sludge did not promote erosion-corrosion. Inconel-600 was resistant to attack. Flow direction appeared to have some effect on the location of corrosion. It is recommended that the concentration of inhibitor be monitored throughout a chemical clean and that an analytical method for determining inhibitor concentrations be developed for this purpose.

job	file	date	report no.
36-598-052	836.3332	September 11, 1989	89-133-K

90-00420/

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EXECUTIVE SUMMARY

EROSION-CORROSION OF BRUCE "A" BLOWDOWN LINES DURING CHEMICAL CLEANING

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Corrosion Chemistry and
Decontamination Project Group
Chemical Research Department

In a Bruce NGS 'A' steam generator tubesheet chemical clean, the solvent must enter and exit the steam generator through the blowdown lines because design limitations prohibit any other access. These blowdowns are 1 or 1 1/2" pipe and are composed of various Inconel and carbon steel alloys. The combination of flow rates, pipe size, configuration, and materials may make the blowdown system susceptible to flow assisted corrosion, commonly called erosion-corrosion.

The purpose of the tests described in this report was to determine if erosion/corrosion could occur in the steam generator blowdown lines during a steam generator chemical clean.

Half-scale models of the 1" blowdown line/elbow/weld configurations were tested in the Chemical Cleaning Loop at a velocity of 5 m/s which is close to the expected maximum velocity in the blowdowns. A proprietary inhibitor, CCI-801, was used. The effects of inhibitor concentration and chemistry of the copper removal step were investigated.

Experiments consisted of one or more sequences each of which consisted of an iron or copper removal step followed by one or two rinses. The loop was purged with N_2 before each iron removal step to remove oxygen.

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Multi-step tests involving both copper and corrosion-inhibited iron removal steps in the presence of sludge did not promote erosion-corrosion, although there appeared to be enhanced corrosion of carbon steel and carbon steel welds.

Coupons exposed to uninhibited iron removal solvent suffered massive attack. Large elongated pits occurred on the carbon steel elbows and welds and shell material. Through-wall pitting of one CS/CS weld occurred in 5 days terminating the test.

About 195 g and 155 g of iron dissolved in the first and second iron removal "steps", respectively. The coupons were not weighed prior to the experiment but a comparison with the average post-test weight of relatively unattacked coupons from the other tests showed a weight loss of about 178 g.

This is much lower than the 349 g estimated from dissolved iron concentrations. The weight loss could have been higher than apparent if deposits had formed on the coupons and/or the coupons were heavier than the "average" weight deduced from the other coupons or sludge had remained in the system from a previous experiment.

The maximum corrosion rate (up to the 2500 μm wall thickness of the pipe), 20 - 23 μm/hr, was greater than the maximum 7-10 μm/hr expected in a static solution/3/. Therefore it would appear that the corrosion was flow assisted. The Inconel-600 pipe appeared virtually unaffected.

Coupons exposed to inhibited iron removal solvent were covered with an orange-brown coating which was probably CCI-801 inhibitor residue.

There was some pitting at the SG/nozzle weld on coupons exposed to 1% CCI-801 inhibited iron removal solutions. There was less attack than in the multi-sequence experiment. It is not clear if this was a result of the copper removal step, sludge added in the multi-sequence experiment, or both. There was a similar amount and type of attack to the 1% inhibited solution for coupons exposed to 1/2% inhibitor iron removal solution. Attack during the 1/4% inhibitor experiment was similar except for more attack in the SG wall and SG/nozzle weld area.

Average carbon steel corrosion rates in inhibited solvent (1/4 - 1%), based on dissolved iron concentrations, ranged from 0.32 to 0.48 μm/hr. The average corrosion rate of carbon steel in 1% CCI-801 inhibited iron removal solvent, based on other work, is 0.05 μm/hr with no magnetite in the solvent, and 0.23 μm/hr with 20 g/L magnetite. The average corrosion rates in these experiments are higher and thus show a possible flow effect which is substantiated by visual inspection of the coupons.

Attack appeared to increase as the inhibitor concentration decreased. An inhibitor concentration of 1% did not completely protect the carbon steel. The effectiveness of the inhibitor may be diminished by flow. Therefore CCI-801 inhibitor offers protection against erosion-corrosion although corrosion rates appear to be higher than what would be expected from bench scale tests.

Inconel-600 appeared unaffected by these tests.

There appeared to be some effect of flow direction on corrosion.

The results in general indicate that the presence of inhibitor is very important to ensure integrity of the steam generator during chemical cleaning.

It is recommended that an analytical method for determining inhibitor concentrations in iron removal solvent be developed. It is recommended that the concentration of inhibitor be monitored throughout the clean. More tests should be performed to determine the minimum inhibitor concentration required to prevent erosion-corrosion in the blowdown lines during a chemical clean and to define the relationship between erosion-corrosion, inhibitor concentration, surface area, sludge loading, and lower velocities.

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To Dr. D. Mills
Director of Research

EROSION-CORROSION OF BRUCE "A"
BLOWDOWN LINES DURING CHEMICAL CLEANING

1.0 INTRODUCTION

In a Bruce NGS 'A' steam generator tubesheet chemical clean, the solvent must enter and exit the steam generator through the blowdown lines because design limitations prohibit any other access. These blowdowns are 1 or 1 1/2" pipe and are composed of various Inconel and carbon steel alloys. The combination of flow rates, pipe size, configuration, and materials may make the blowdown system susceptible to flow assisted corrosion, commonly called erosion-corrosion.

Erosion-corrosion tends to occur in areas of high turbulence or where there is a sudden change in flow direction. It depends on the metal solubility and mass transfer rates of metal into solution. The mass transfer rate is proportional to the concentration gradient of dissolved metal between the metal surface and bulk solution so that metal already in solution would tend to decrease erosion-corrosion. Oxygen in solution tends to decrease erosion-corrosion because protective surface oxides can form more rapidly.

Erosion-corrosion is a concern in chemical cleaning since the solvents, the iron-removal solvent in particular, can be corrosive. A corrosion inhibitor, CCI-801, is added to the iron-removal solvent but it is not known how well this inhibitor would perform in areas of turbulence or high solvent velocity.

Previous tests conducted in the Flow Visualization Loop/1/ had shown that the optimum inlet/outlet configuration for ensuring flow across the sludge pile consisted of the diametral blowdown lines as solvent inlets and four of the twelve peripheral blowdown lines as solvent outlets. All the peripheral blowdowns could be used as solvent outlets if isolation of the peripheral blowdowns from each other was not feasible. The maximum total flowrate during a chemical clean is expected to be about 11

L/s/2/. Expected velocities in the 1" peripheral blowdowns for this flow rate are 1.8 m/s (5.9 ft/s) if all 12 peripherals are used and 5.42 m/s (17.8 ft/s) if only 4 peripheral blowdowns are used. The corresponding velocity in the 1 1/2" diametral blowdowns is 4.82 m/s (15.8 ft/s).

At these velocities, erosion-corrosion may be of concern, particularly in the region of welds and elbows. The most susceptible part of the blowdown line is in the blowdown nozzle/ thick shell/ I-600 elbow/ I-600 tube assembly in the steam generator where there are two ninety-degree changes in flow direction. Other areas include the I-600 elbow at the boxheader and the holes in boxheader. Corrosion of the holes in the boxheader is not of great concern.

2.0 PURPOSE

The purpose of the tests described in this report was to determine if erosion/corrosion could occur in the steam generator blowdown lines during a steam generator chemical clean.

3.0 TEST PROGRAM

Half-scale models of the 1" blowdown line/elbow/weld configurations were tested in the Chemical Cleaning Loop at a velocity of 5 m/s. This velocity, limited by the loop design, is close to the expected maximum velocity in the blowdowns (4.8 m/s or 5.4 m/s depending on the inlet/outlet configuration used) during a chemical clean. This configuration would also effectively represent the I-600 elbow at the boxheader. A proprietary inhibitor, CCI-801 was used. The worst case scenario was thought to occur with clean Fe removal solution, no available sludge, and a solvent devoid of inhibitor. However, bench-scale tests showed corrosion rates to increase if there was magnetite in the solvent/3/. The effects of inhibitor concentration and chemistry of the copper removal step were investigated.

3.1 Equipment

3.1.1 Chemical Cleaning Loop

All tests were performed in the Chemical Cleaning Loop (Figure 1). It is a 316 SS loop with flanged fittings, a 36 L reservoir, and a centrifugal pump. Total solvent volume in the loop was 55 L for these tests. Flow was measured using orifice plates and a differential pressure cell. Solution could be routed at known flowrates through the corrosion coupons, a bypass, or both

simultaneously. The system could be purged with N_2. Temperature was monitored continually. The loop could be heated by a heater in the reservoir and by heater tape around the reservoir. It could be cooled by a heat exchanger in the piping. In the iron removal step, temperature was controlled by the heaters. In the copper removal step, maximum and minimum temperatures were controlled by the heat exchanger and heaters respectively.

3.1.2 Corrosion Coupons

The corrosion coupons were half-scale replicas of the actual configuration in the steam generator. Figure 2 shows the design of the coupons. The blowdown lines are connected to the exterior blowdowns through the shell by welded elbows and a nozzle. Table 1 shows the materials used.

TABLE 1 Blowdown Assembly Materials

Part	Material
Interior blowdown pipe and elbow	I-600
Exterior blowdown pipe and elbow	SA 106 Gr B
Blowdown nozzle	SA 105 Gr 2
Thickshell	SA 516 - 70

The coupons were welded using the same welding procedures as were used in the station. This resulted in some relatively poor welds of the carbon steel elbow to carbon steel pipe which resulted in constricting the diameter of the pipe at that area. Normally, a welding procedure different from the one used at the station would be used for 1/2" pipe. Figure 1 shows how the coupons were inserted into the loop so that in any given experiment, one coupon would represent the inlet configuration and the other would represent the outlet configuration.

3.2 Experiments

Table 2 lists the composition of the iron and copper removal solvents and the operating temperatures.

TABLE 2 Solvent Composition

Copper Removal Solvent	Iron Removal Solvent	Rinse
5 % EDTA En to pH 9 2 % H_2O_2 20 to 35°C	10 % EDTA 1 % N_2H_4 * 1 % CCI-801 corrosion inhibitor NH_3 to pH 7 93°C * inhibitor concentration varied depending on experiment	NH_3 to pH 9-9.5

Experiments consisted of one or more sequences each of which consisted of an iron or copper removal step followed by one or two rinses. The loop was purged with N_2 before each iron removal step to remove oxygen in the gas space in the reservoir.

Table 3 lists all experiments performed.

TABLE 3 Erosion-corrosion Experiments

Exp. #	Purpose	Step Sequence (days)
1	simulation of multi-step chemical clean	Cu Rx2 Fex3 Rx2 Cu Rx2 1 1 7 1 1 1days
2	effect of no inhibitor	Fex3 R 6 1 days
3	effect of 1% CCI-801	Fe Rx2 9 1 days
4	effect of 0.5% CCI-801	Fe R 11 1 days
5	effect of 0.25% CCI-801	Fe R days 12 1 days

R = rinse
Fe = Iron Removal step
Cu = Copper Removal step
x2(3) = step carried out twice (three times)

Powdered Nanticoke sludge (31.6% Cu, 38.5% Fe), weighing 250 g was added at the beginning of experiment 1. An addition of 500g sludge had been made in a previous experiment. Most of this sludge probably remained in the system for experiment 1. For calculation purposes, experiment 1 was assumed to have 500g sludge. Up to 4 H_2O_2 additions were made during the course of a copper removal step at 3 hour intervals starting at the beginning of the experiment. N_2H_4 was monitored throughout experiment 4. A single addition was made in this experiment to bring the N_2H_4 concentration to 1%.

All coupons were weighed after the experiments.

3.3 Sampling and Analyses

Water samples were collected daily. The temperature was monitored continually. The pH of each sample was taken. H_2O_2 was not monitored since its behaviour in the loop had been characterized in other tests/3/. N_2H_4 was monitored in one test only to determine if it had decomposed to below 0.5%, the minimum concentration specified to prevent ferric ion corrosion/3/. It had not, and so was not monitored in other tests (see Figure 6).

3.4 Coupon Examination

Most of the coupons were examined using a fibrescope before being sectioned. All coupons were sectioned by EDM and photographed.

4.0 RESULTS AND DISCUSSION

Corrosion results are summarized in Tables 4 and 5. Figures 3 to 7 show the pH, dissolved iron and dissolved copper concentrations with time for all experiments and hydrazine versus time for experiment 4 (Figure 6). Figures 8 to 30 show photographs of the coupons. Fibrescope examinations and photographs of the sectioned coupons are shown. Experiments are discussed individually.

TABLE 4 Coupon Corrosion Description

Exp #	Experiment Description	Coupon #	Flow Dir*	Coupon Description
1	multi-sequence 1% CCI-801 inhibitor	1	a	- pitting on CS elbow, SG wall and nozzle and nozzle/CS weld - I-600 unattacked
		3	b	- as in 1 plus pitting downstream of CS elbow/pipe weld
2	iron removal no inhibitor	5	a	- large, somewhat elongated pits on CS elbow and nozzle - smaller pits on SG wall - extensive attack of SG/nozzle, nozzle/CS elbow, and CS elbow/pipe welds - I-600 unattacked
		6	b	- through-wall pit at nozzle /CS elbow weld - as in 5 except CS elbow appears less pitted and shell is more pitted - I-600 unattacked
3	iron removal 1% CCI-801 inhibitor	7,8	a,b	- some pitting at SG/nozzle weld (more on 7 than on 8) - pitting(?) and discolouration of CS elbow and pipe (less on 7 than on 8) - I-600 discoloured but otherwise unattacked
4	iron removal 0.5% CCI-801 inhibitor	9,10	a,b	- same as in 7 & 8 but slightly less weld pitting on 10 than 9
5	iron removal 0.25% CCI-801 inhibitor	11,12	a,b	- same as in 7 & 8 with more attack in SG and SG/nozzle weld area and deeper pits on 12 - I-600 discoloured but otherwise unattacked

* Flow direction: a: into steam generator (CS --> I-600)
b: out of steam generator (I-600 --> CS)

TABLE 5 Coupon Corrosion Rates

Exp #	Coupon #	Undescaled post experiment weight (g)	Weight Loss compared to average coupon weight*+(g)	Weight dissolved Fe (g)	Corrosion rate μm/hr by wt loss	Corrosion rate μm/hr by diss Fe
1	1	1449	-3 total-22	101	-	-**
	3	1465	-19			
2	5	1371	75 total 178	349	6.9 @	13.6
	6	1343	103			
3	7	1469	-23 total-18	18	-	0.32
	8	1441	5			
4	9	1425	21 total 25	17	0.53	0.36
	10	1442	4			
5	11	1454	-8 total 13	30	0.21	0.48
	12	1425	21			

* - reading means weight gain

** dissolved Fe is not solely an indication of corrosion because sludge was added to solution before experiment

@ estimated corrosion rate of through-wall pit = 20 - 23 μm/hr

+ average coupon weight = sum of post experiment weights of coupons 1, 2, 7, 8, 9, 10, 11, 12 divided by # of coupons

4.1 Effect of Copper and Iron Removal Steps (Experiment 1)

In experiment 1 the pH in the copper removal steps decreased from 9 to 5.9 and from 9 to 7.7 in the first and second copper removal steps respectively, as shown in Figure 3. The pH of the iron removal steps varied from 7.2 to 6.4.

The first copper removal step removed approximately 102 g of copper, about 66% of the estimated total available copper. The second copper removal step removed only 24 g of copper for a total removal of 81% of the estimated available copper in the sludge.

Seventy grams of iron or about 36% of the total estimated available in the sludge was removed in the first iron removal step, and 36 g of iron was removed in the second iron removal step for a total of 55% of the estimated available iron in the sludge.

There was some pitting on the CS elbows, SG wall, nozzle, and nozzle to CS weld as is shown in Figures 9 to 14. The "outlet" coupon (#3) had some pitting downstream of the CS elbow/pipe weld.

4.2 Effect of Inhibitor

4.2.1 Effect of No Inhibitor (Experiment 2)

The "single" iron removal step was, as a result of equipment problems, three iron removal "steps" without rinses (see Figure 4). The coupons were exposed to about 2 days of static iron removal solvent at the end of the first "step" due to an emergency shutdown over a weekend. The experiment duration was thus considered to be 5 days.

The pH increased from 7 to about 8 in the first and third "steps". The second "step" was too short to record any changes.

Coupons from the test with no inhibitor suffered massive attack as is illustrated in Figures 15 to 20. Large elongated pits occurred on the carbon steel elbows and welds and shell material. Through wall pitting of one CS/CS weld occurred in 5 days terminating the test.

The weld filler (exposed when weld was drilled out) at the shell to nozzle weld did not appear corroded, but the interfaces between the weld and the carbon steel were badly corroded. The CS elbow in the outlet configuration was less attacked than its counterpart in the inlet configuration showing a possible flow effect. Conversely, there was more pitting on the shell in the outlet configuration than in the inlet configuration. This may imply that CS attack is less downstream when there is no inhibitor.

About 195 g and 155 g of iron dissolved in the first and second iron removal "steps", respectively. The coupons were not weighed prior to the experiment but a comparison with the average post-test weight of coupons from the other tests showed a weight loss of about 178 g.

This is much lower than the 349g estimated from dissolved iron concentrations. If the rest of the iron in the sludge from the previous experiment (see section 4.1) had remained and then dissolved in this experiment, it would account for at least 90 g. The actual weight loss could have been higher if deposits had formed on the coupons and/or the coupons were heavier than the "average" weight deduced from the other coupons.

The maximum corrosion rate (up to the 2500 μm wall thickness of the pipe), 20 - 23 μm/hr, was greater than the maximum 7 - 10 μm/hr expected in a static solution/3/. Therefore it would appear that the corrosion was flow assisted. The elongated shape of the pits substantiates this observation.

The Inconel-600 pipe appeared virtually unaffected although photographs taken through the fibrescope indicated that there may have been some pitting or deposition.

4.2.2 Effect of Inhibitor (Experiments 3, 4, 5)

The coupons were covered with an orange-brown coating which was probably CCI-801 inhibitor residue at the end of all experiments containing inhibitor (see Figures 21 to 30).

The pH of the 1, 1/2, and 1/4% inhibitor tests varied from 7 to 6.6, 7.5, and 6.6 respectively (Figures 5, 6, and 7).

In the 1% inhibitor experiment, there was some pitting at the SG/nozzle weld as shown in Figures 21 to 26. The SG/nozzle weld outlet configuration was slightly less pitted than its counterpart in the inlet configuration. The attack on the CS elbow was slightly less in the inlet configuration than in the outlet. There was less attack than in the multi-sequence experiment. It is not clear if this was a result of the copper removal step, sludge added in the multi-sequence experiment, or both. Other work/3/ has shown that corrosion in the Fe removal solvent is greater if it contains dissolving magnetite.

In the 1/2% inhibitor experiment, there was a similar amount and type of attack as in the 1% inhibitor experiment (Figures 27 and 28). In both cases, the attack in the SG wall and SG/nozzle weld area was slightly greater in the inlet configuration than in the outlet configuration. Attack during the 1/4% inhibitor experiment was similar except for more attack in the SG wall and SG/nozzle weld area (Figures 29 and 30). This attack is probably related to the flow/turbulence patterns.

The weights of iron removed during these three tests were 18, 17, and 30 g respectively giving average corrosion rates of 0.32, 0.36, and 0.48 lm/hr respectively. The average corrosion rate of carbon steel in 1% CCI-801 inhibited Fe removal solvent is 0.05 m/hr with no magnetite, and 0.23 lm/hr with 20 g/L dissolving magnetite/3/. The average corrosion rates in these experiments are higher and thus show a possible flow effect.

Attack appeared to increase as the inhibitor concentration decreased. An inhibitor concentration of 1% did not completely protect the carbon steel. The effectiveness of the inhibitor may be diminished by flow.

5.0 CONCLUSIONS

1. Test coupons of the steam generator shell/blowdown area showed massive erosion-corrosion in the iron removal solution when no inhibitor was present at a velocity of about 5 m/s.

2. Test coupons immersed in iron removal solution with 1/4 to 1% CCI-801 inhibitor did not show signs of gross erosion-corrosion. Pitting was observed. Flow direction appears to have some effect on the location of corrosion in the blowdown lines. Therefore CCI-801 inhibitor offers protection against erosion-corrosion although corrosion rates appear to be higher than what would be expected from low flow bench scale tests. The amount of attack appears to decrease as the concentration of inhibitor increases as shown from visual inspection and indirect estimates of corrosion rate.

3. Multi-step tests involving both copper and corrosion-inhibited iron removal steps in the presence of sludge did not promote erosion-corrosion, although there appeared to be enhanced corrosion of carbon steel and carbon steel welds.

4. I-600 appears resistant to corrosion in both iron and copper removal solvents.

5. The results of these experiments indicate that the presence of inhibitor is very important to ensure integrity of the steam generator during chemical cleaning. Therefore the inhibitor concentration should be monitored during a chemical clean. A technique for measuring the inhibitor concentration should be developed for use on-site during the clean.

6.0 RECOMMENDATIONS

It is recommended that an analytical method for determining inhibitor concentrations in iron removal solvent be developed. It is recommended that the concentration of inhibitor be monitored throughout the clean. More tests should be performed to better define the relationship between erosion-corrosion or flow assisted corrosion, inhibitor concentration, surface area, sludge loading, and lower velocities.

7.0 ACKNOWLEDGEMENTS

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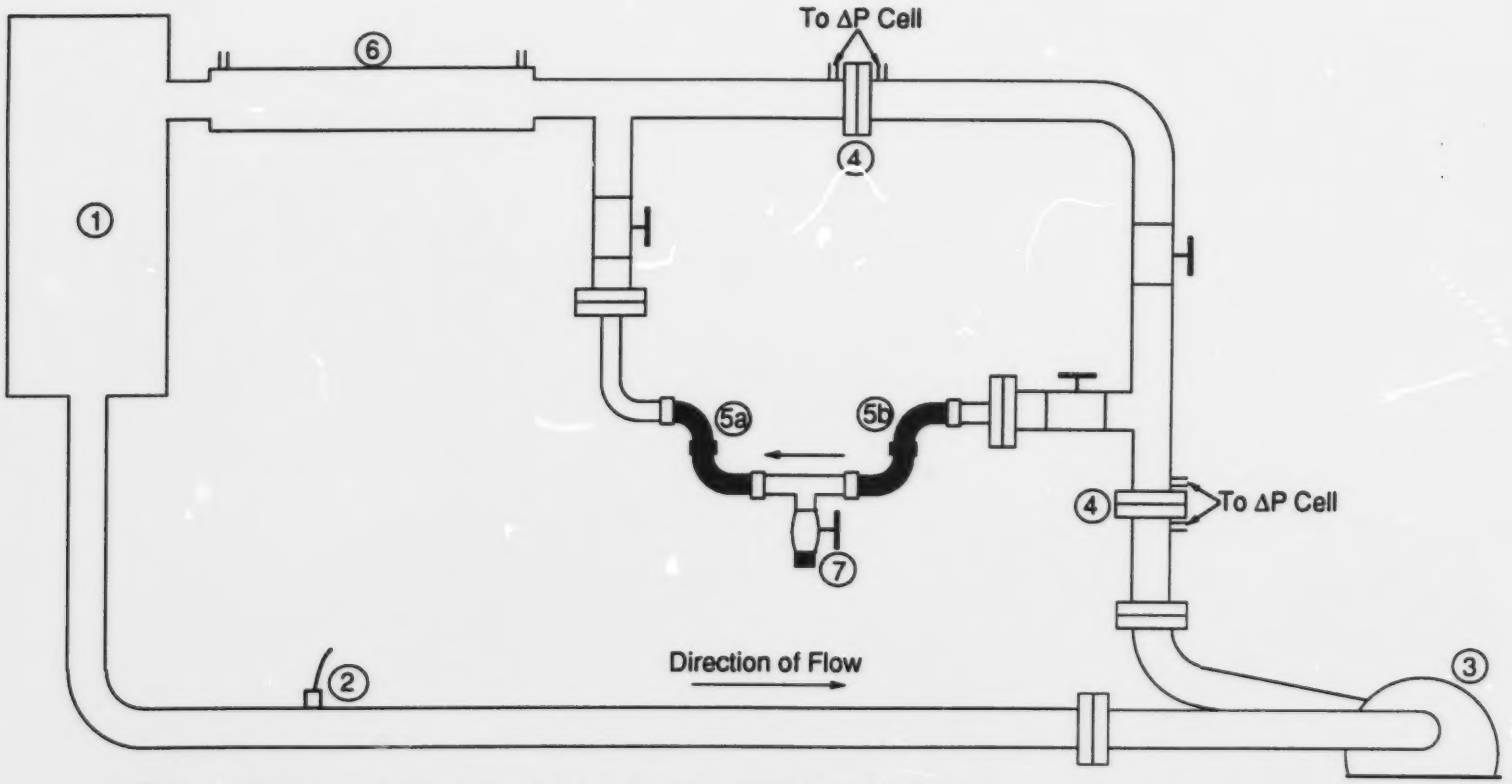
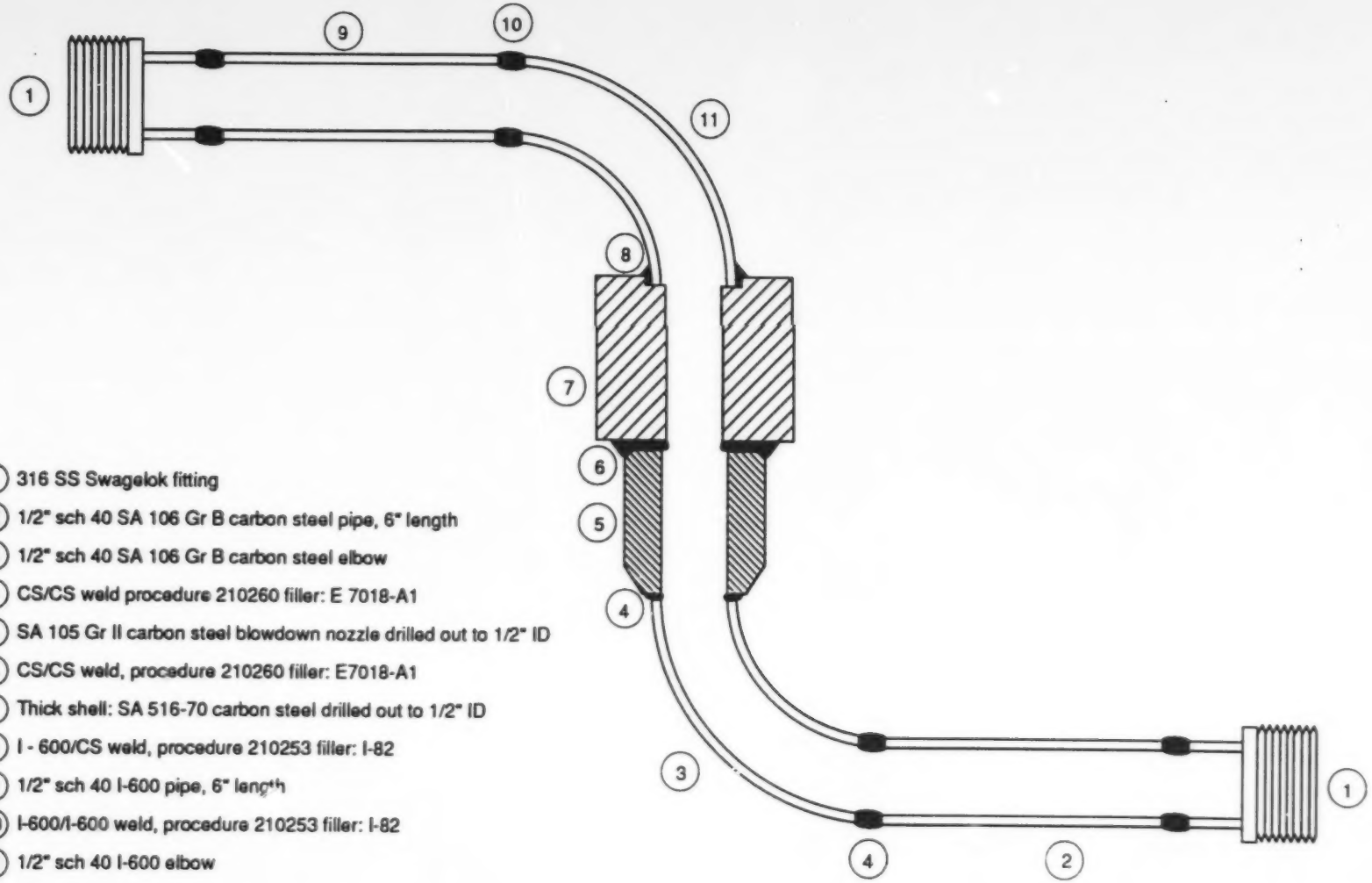


① 36 L reservoir containing immersion heater and wrapped with heating tape
② In-line pH probe
③ Centrifugal pump
④ Orifice plate
⑤ Erosion - corrosion coupons (shaded) 5a: Outlet configuration
5b: Inlet Configuration
⑥ Heat exchanger
⑦ Sampling line/drain

FIGURE 1
CHEMICAL CLEANING LOOP SCHEMATIC



1. 316 SS Swagelok fitting
2. 1/2" sch 40 SA 106 Gr B carbon steel pipe, 6" length
3. 1/2" sch 40 SA 106 Gr B carbon steel elbow
4. CS/CS weld procedure 210260 filler: E 7018-A1
5. SA 105 Gr II carbon steel blowdown nozzle drilled out to 1/2" ID
6. CS/CS weld, procedure 210260 filler: E7018-A1
7. Thick shell: SA 516-70 carbon steel drilled out to 1/2" ID
8. I - 600/CS weld, procedure 210253 filler: I-82
9. 1/2" sch 40 I-600 pipe, 6" length
10. I-600/I-600 weld, procedure 210253 filler: I-82
11. 1/2" sch 40 I-600 elbow

FIGURE 2
BLOWDOWN / NOZZLE / SHELL / BLOWDOWN COUPON ASSEMBLY

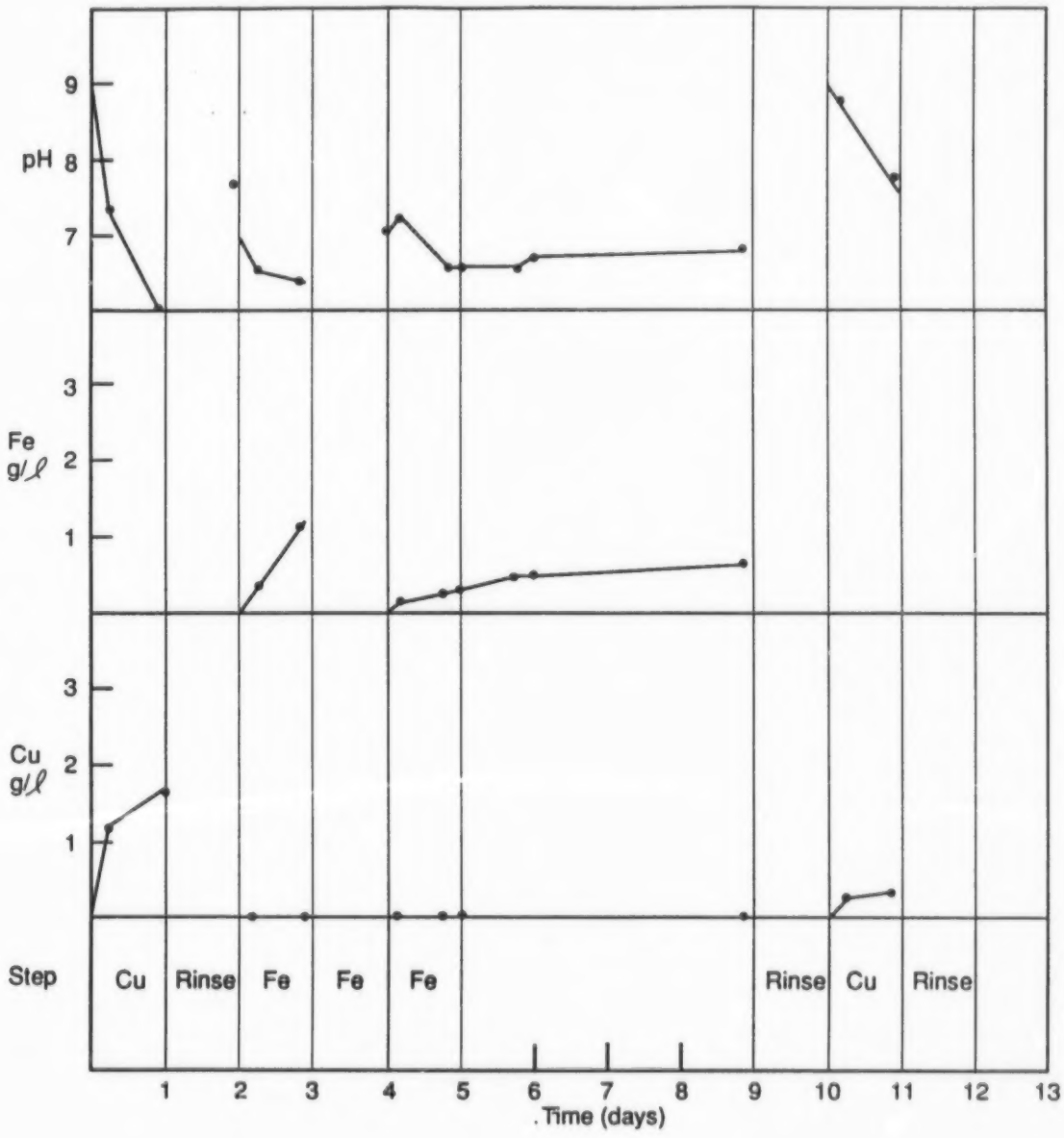


FIGURE 3
EXPERIMENT 1: SIMULATION OF MULTI-STEP CHEMICAL CLEAN
VARIATION OF pH, IRON AND COPPER CONCENTRATIONS WITH TIME

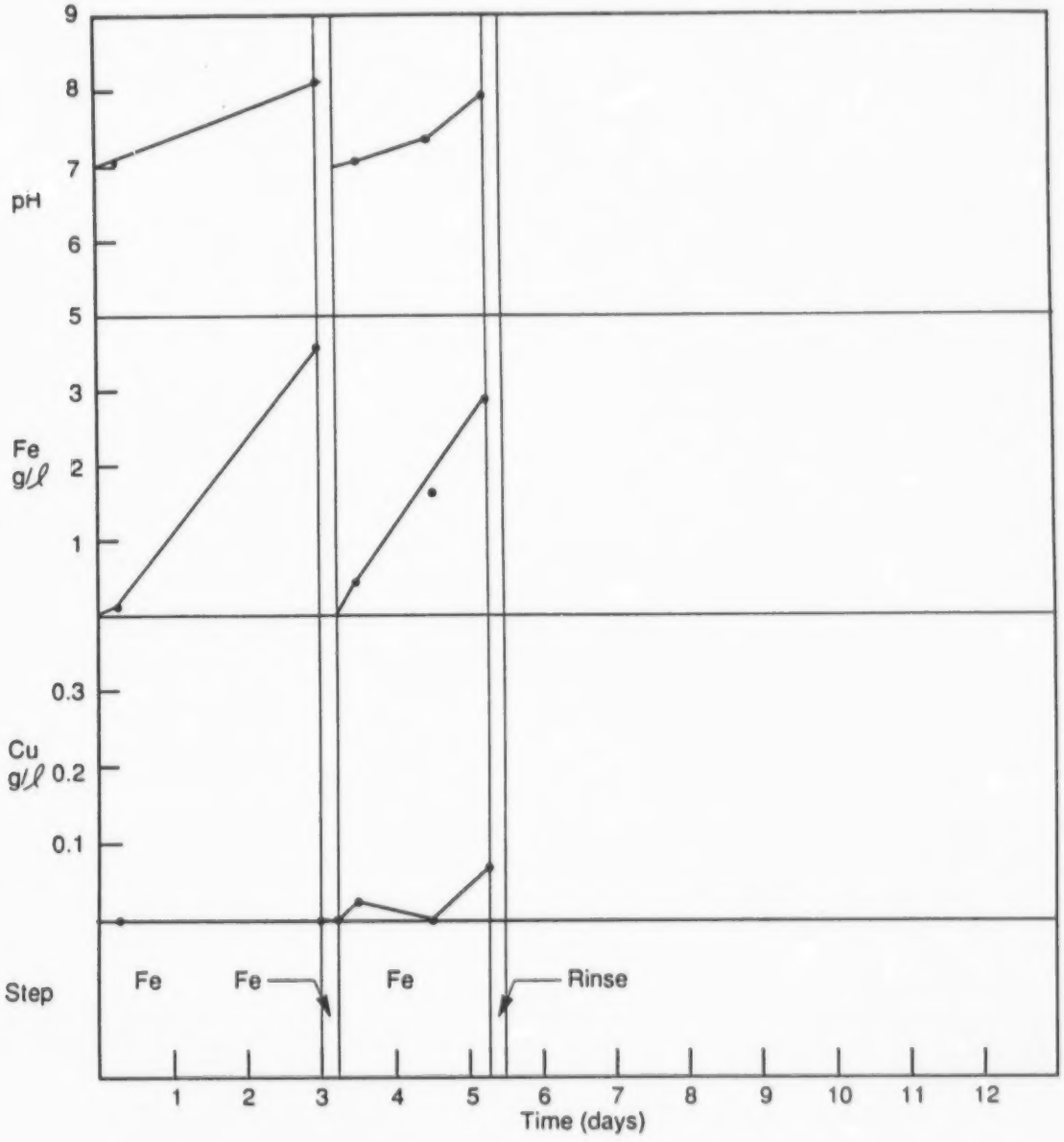


FIGURE 4
EXPERIMENT 2: EFFECT OF NO INHIBITOR
VARIATION OF pH, IRON AND COPPER CONCENTRATION WITH TIME

89-133
179933-C9-RD

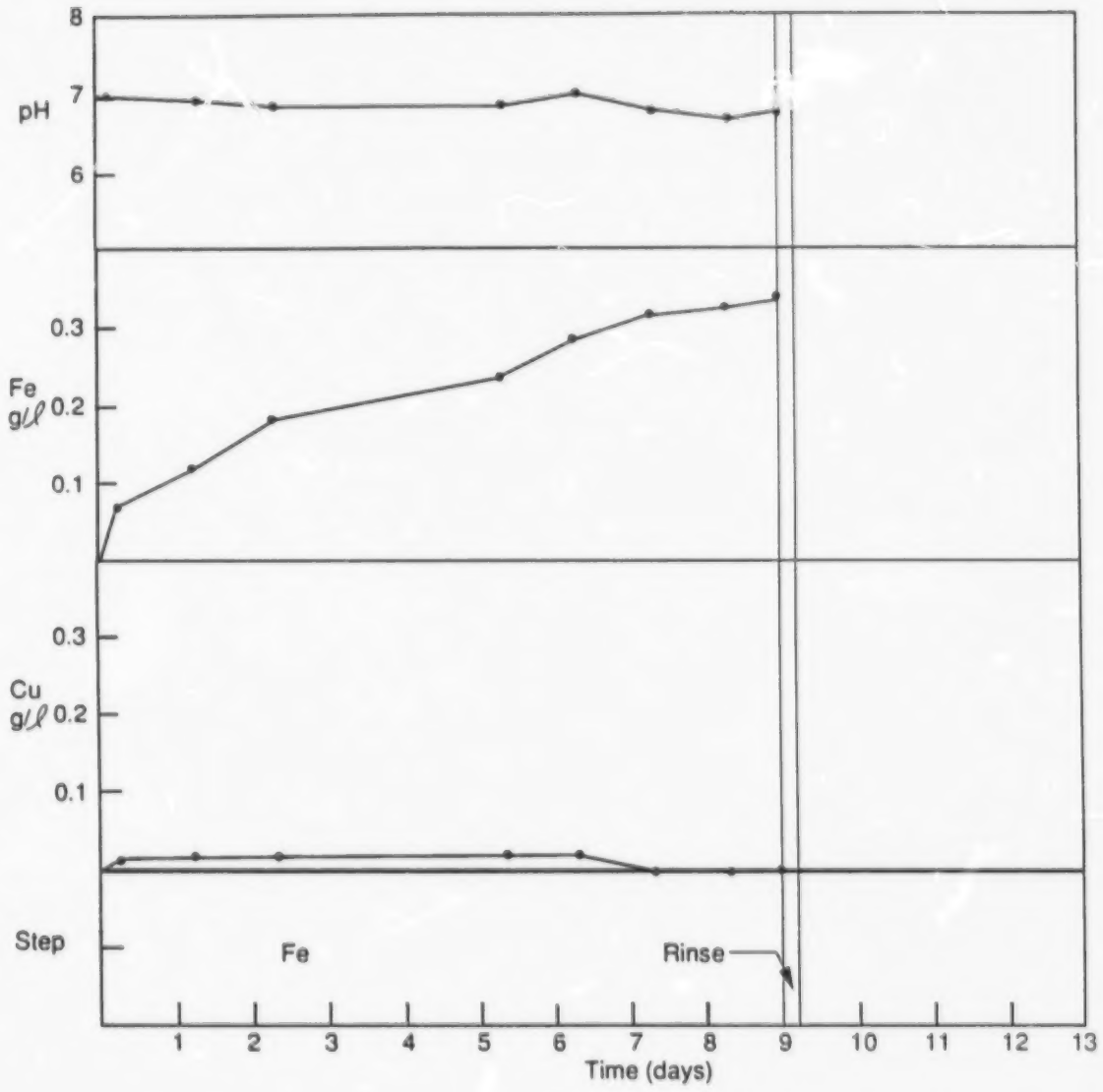


FIGURE 5
EXPERIMENT 3: EFFECT OF 1% CCI-801
VARIATION OF pH , IRON AND COPPER CONCENTRATIONS WITH TIME

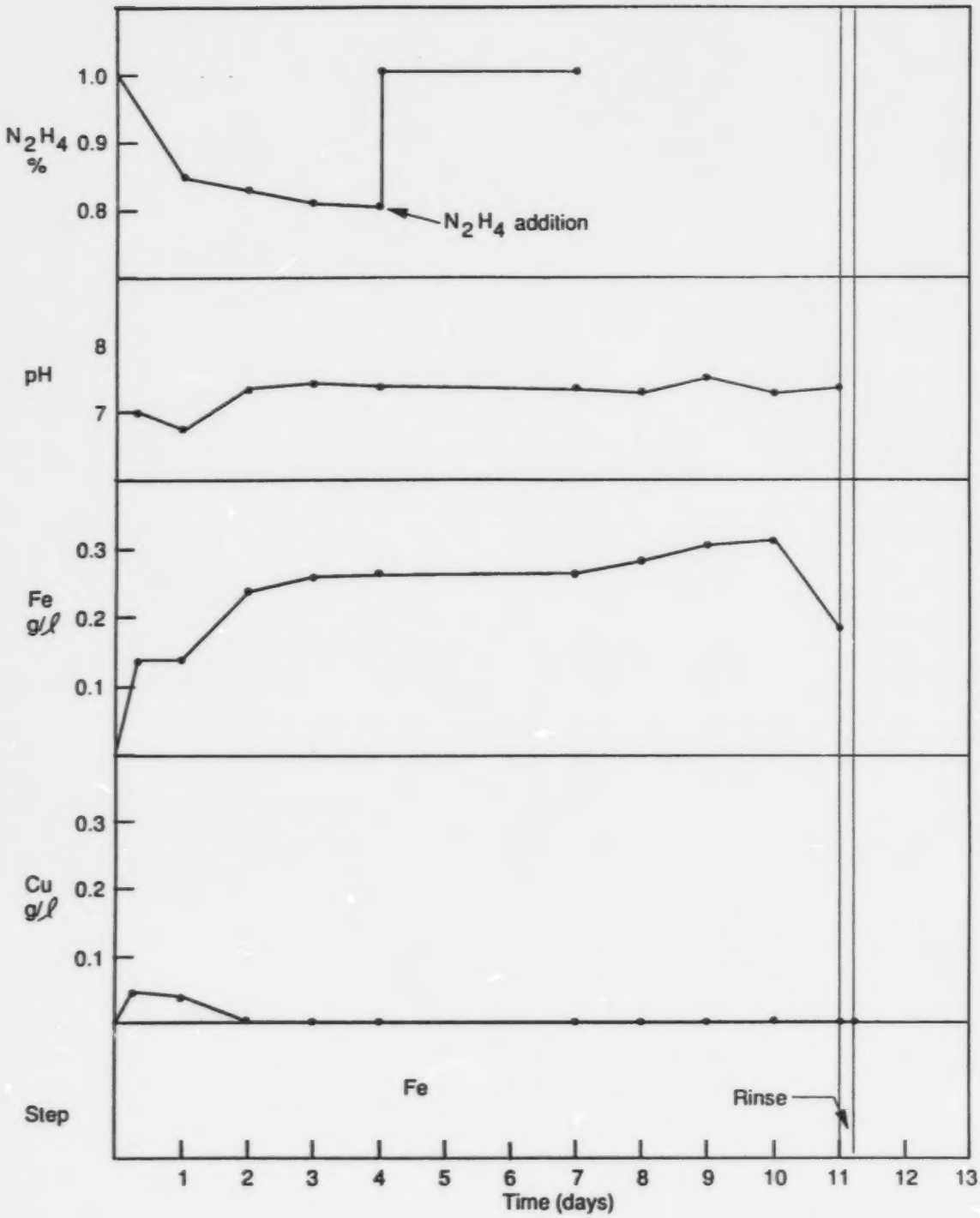


FIGURE 6

EXPERIMENT 4: EFFECT OF 0.5% CCI-801
VARIATION OF pH, IRON AND COPPER CONCENTRATIONS WITH TIME

89-133
179935-C9-RD

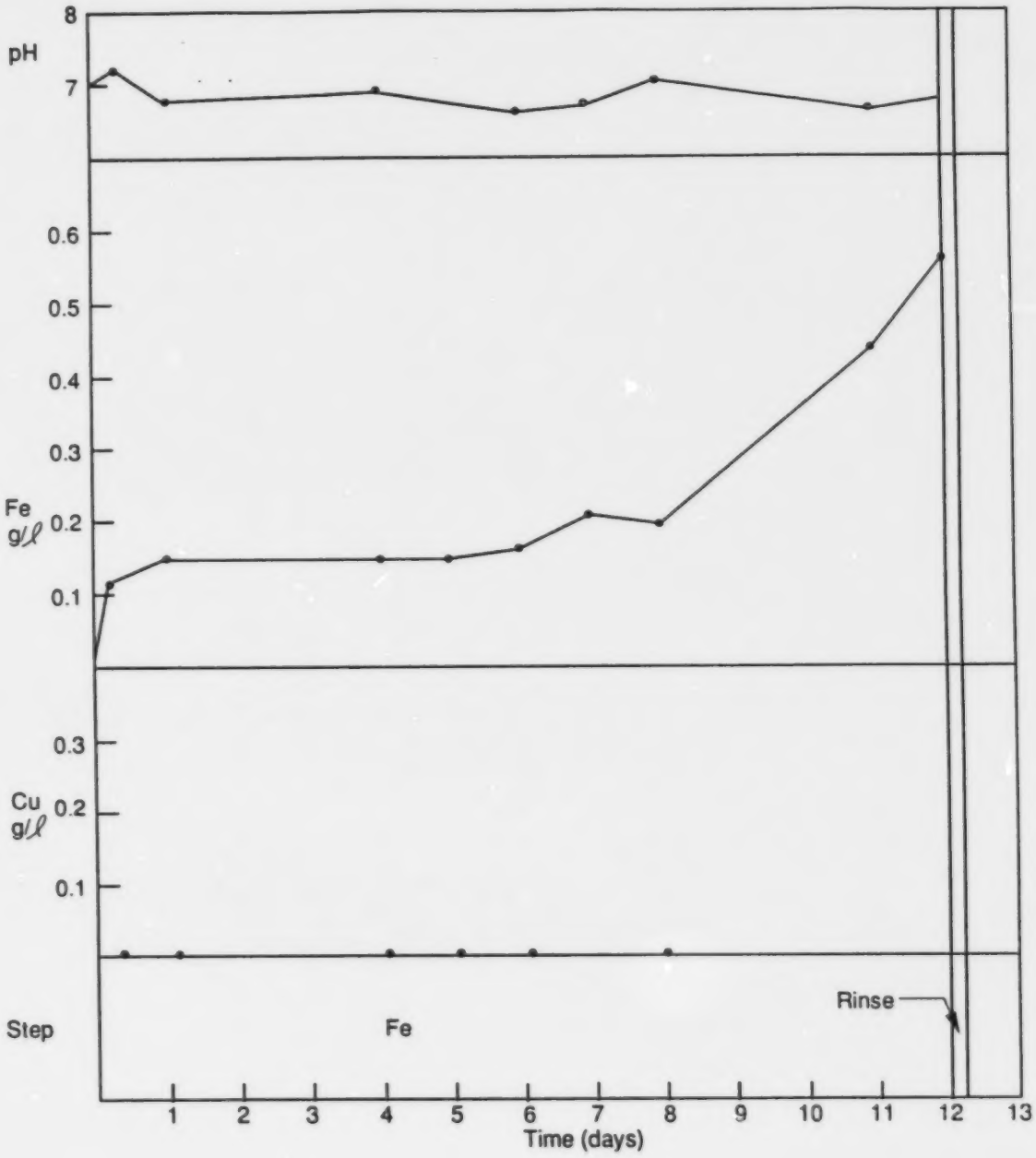


FIGURE 7
EXPERIMENT 5: EFFECT OF 0.25% CCI-801
VARIATION OF pH, IRON AND COPPER CONCENTRATIONS WITH TIME

89-133
179936-C9-RD

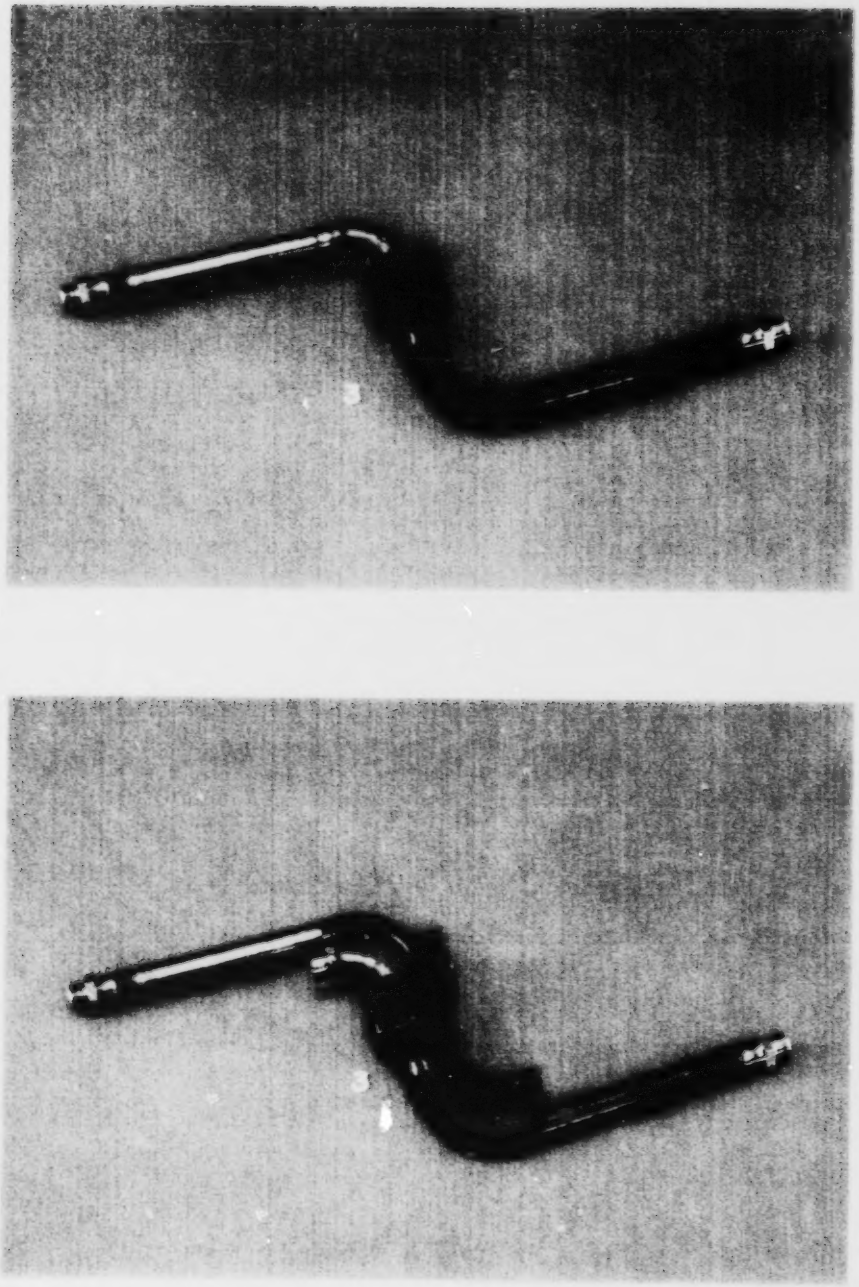
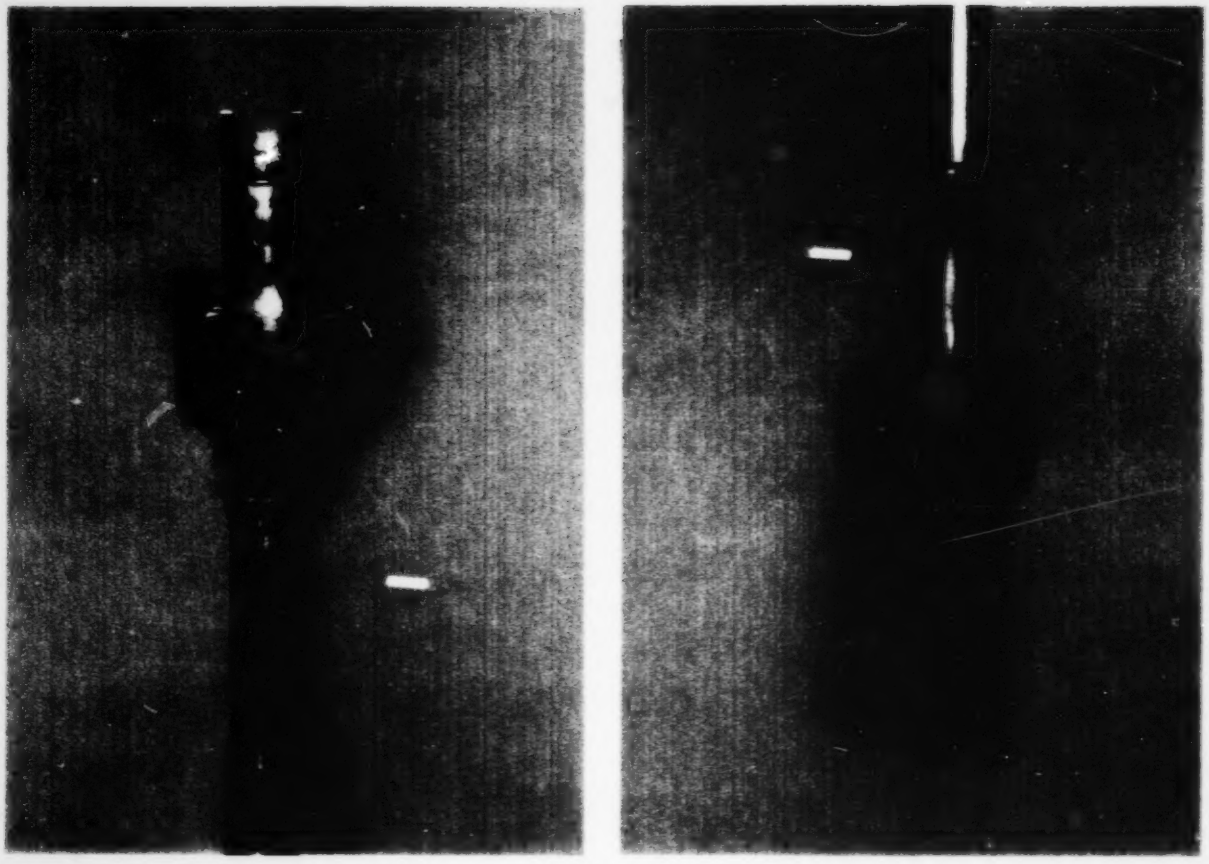


FIGURE 8
EROSION - CORROSION TEST COUPON
DETAIL OF CUT BY EDM

89-133
179937-C8-RD



Test Conditions: Multi-step Test with CCI-801 Inhibitor

Flow Direction
(Coupon Orientation as Shown in above Photograph)

FIGURE 9
EROSION - CORROSION TEST COUPON #1

89-133
179938-C9-RD

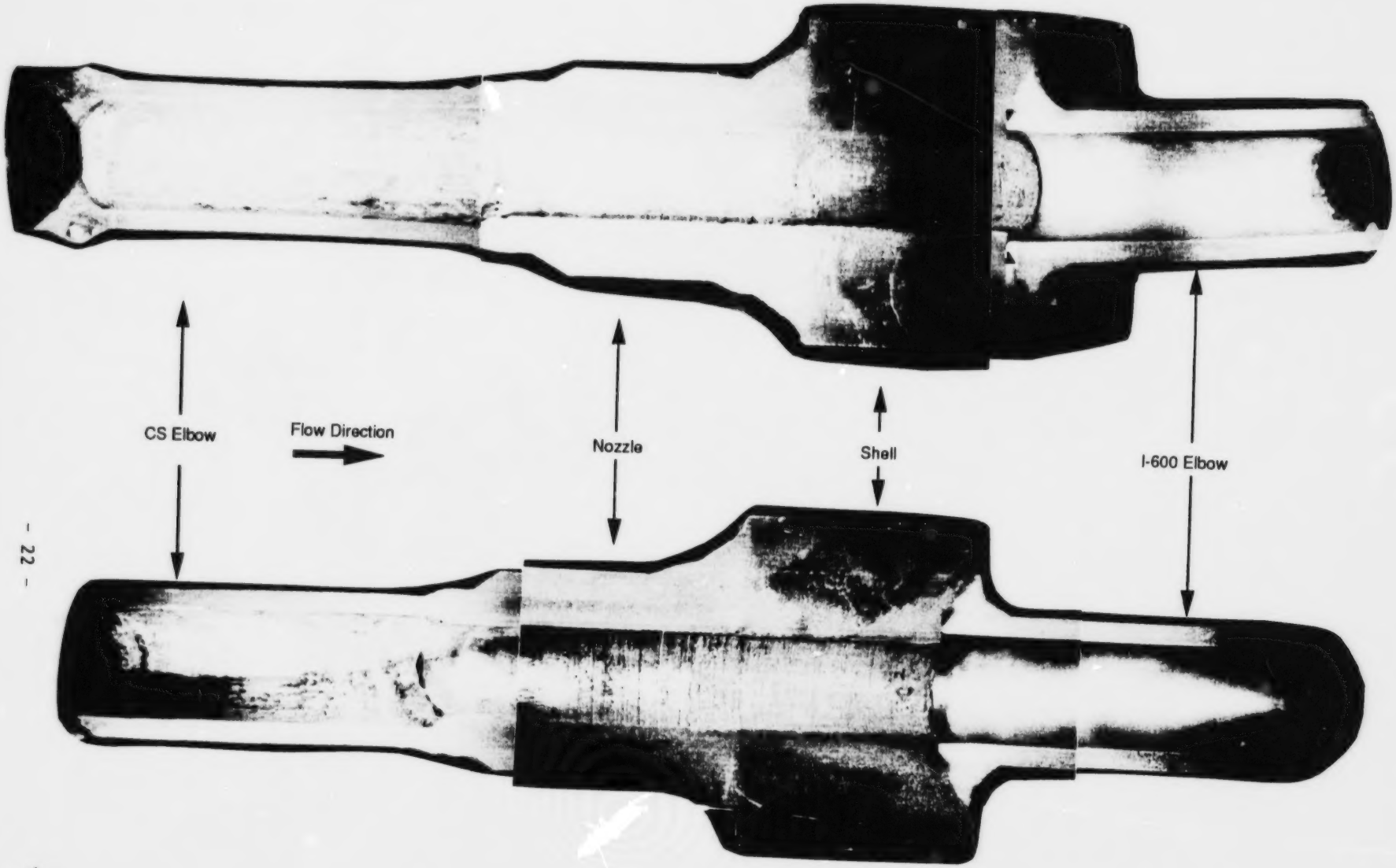


FIGURE 10
EROSION - CORROSION TEST COUPON #1

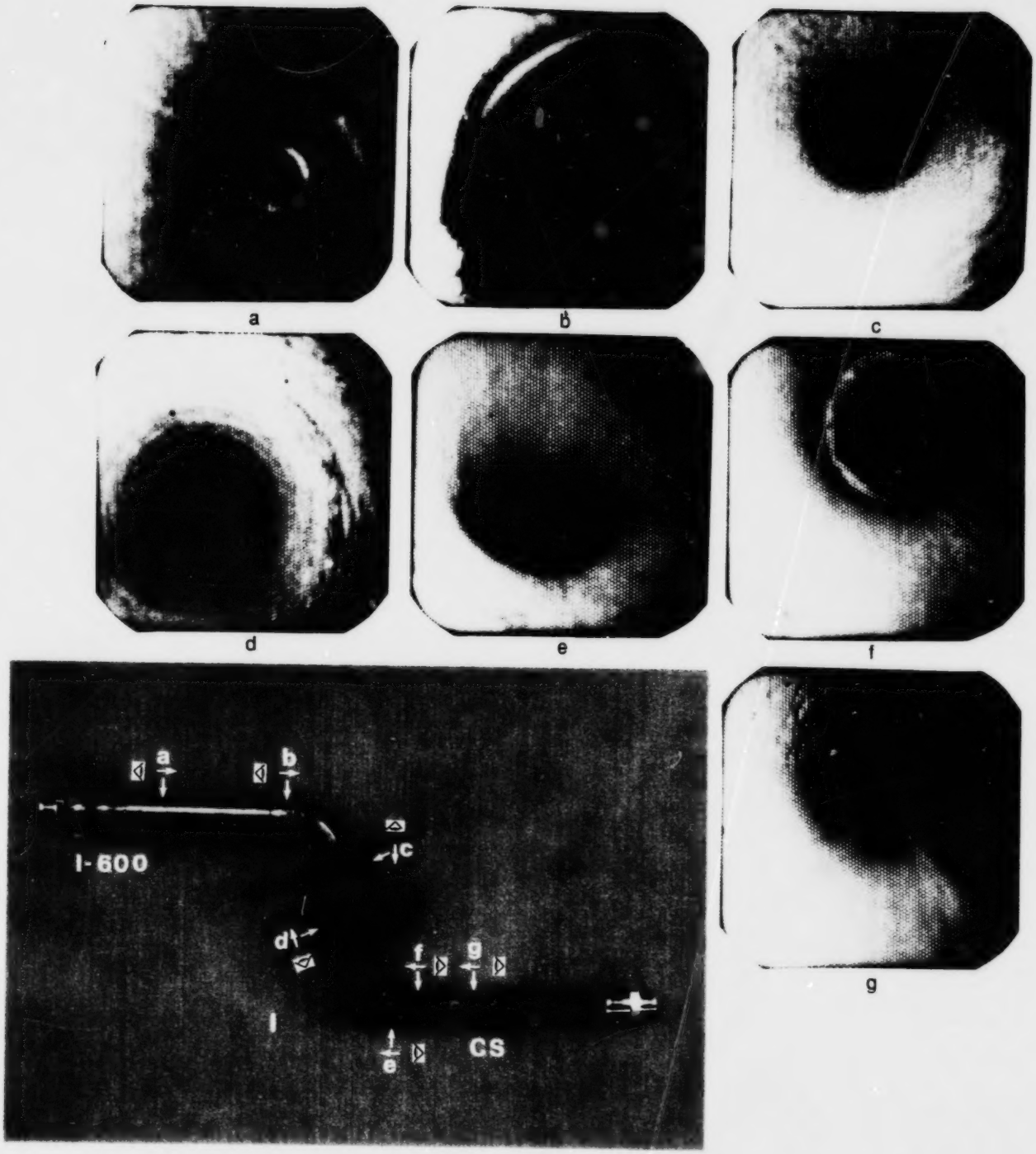
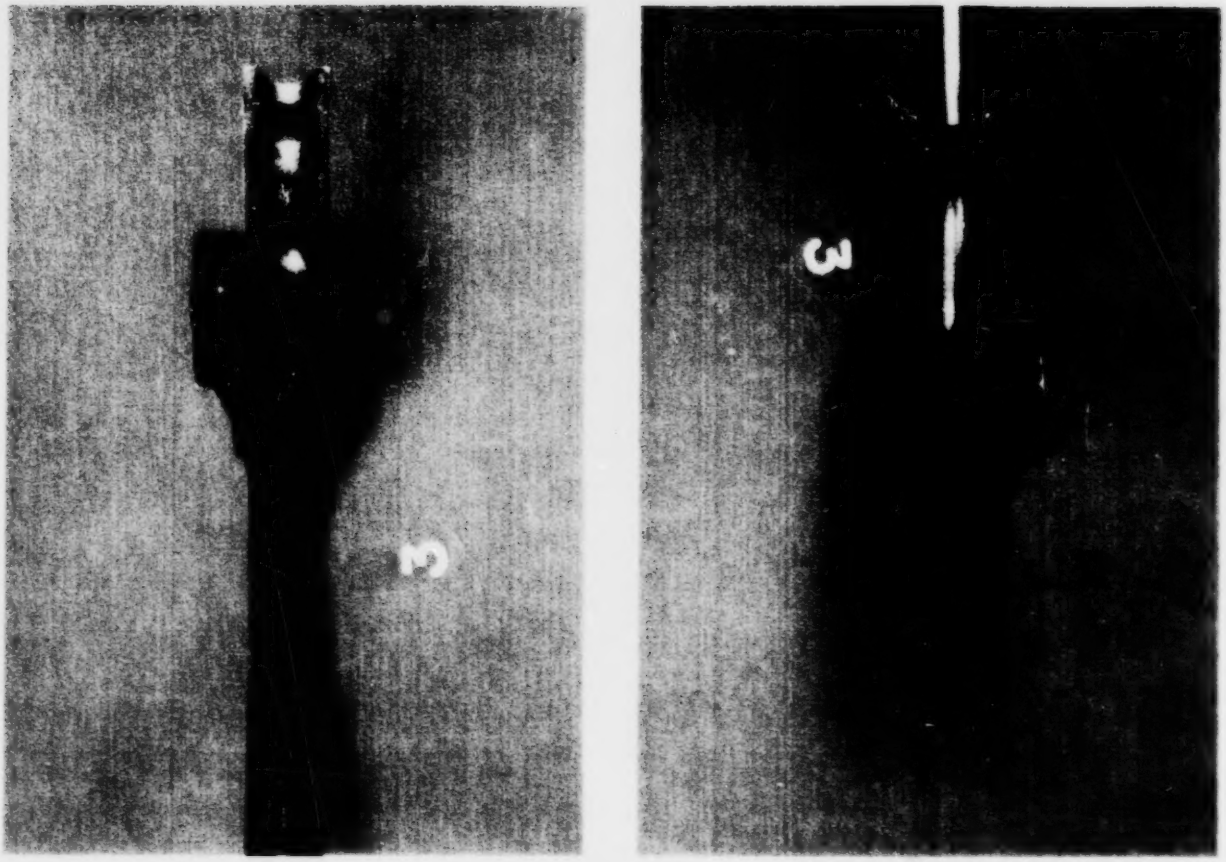


FIGURE 11
FIBRESCOPE EXAMINATION OF COUPON #1



Test Conditions: Multi-step Test with CCI-801 Inhibitor

Flow Direction
(Coupon Orientation as Shown in above photographs)

FIGURE 12
EROSION - CORROSION TEST COUPON #3

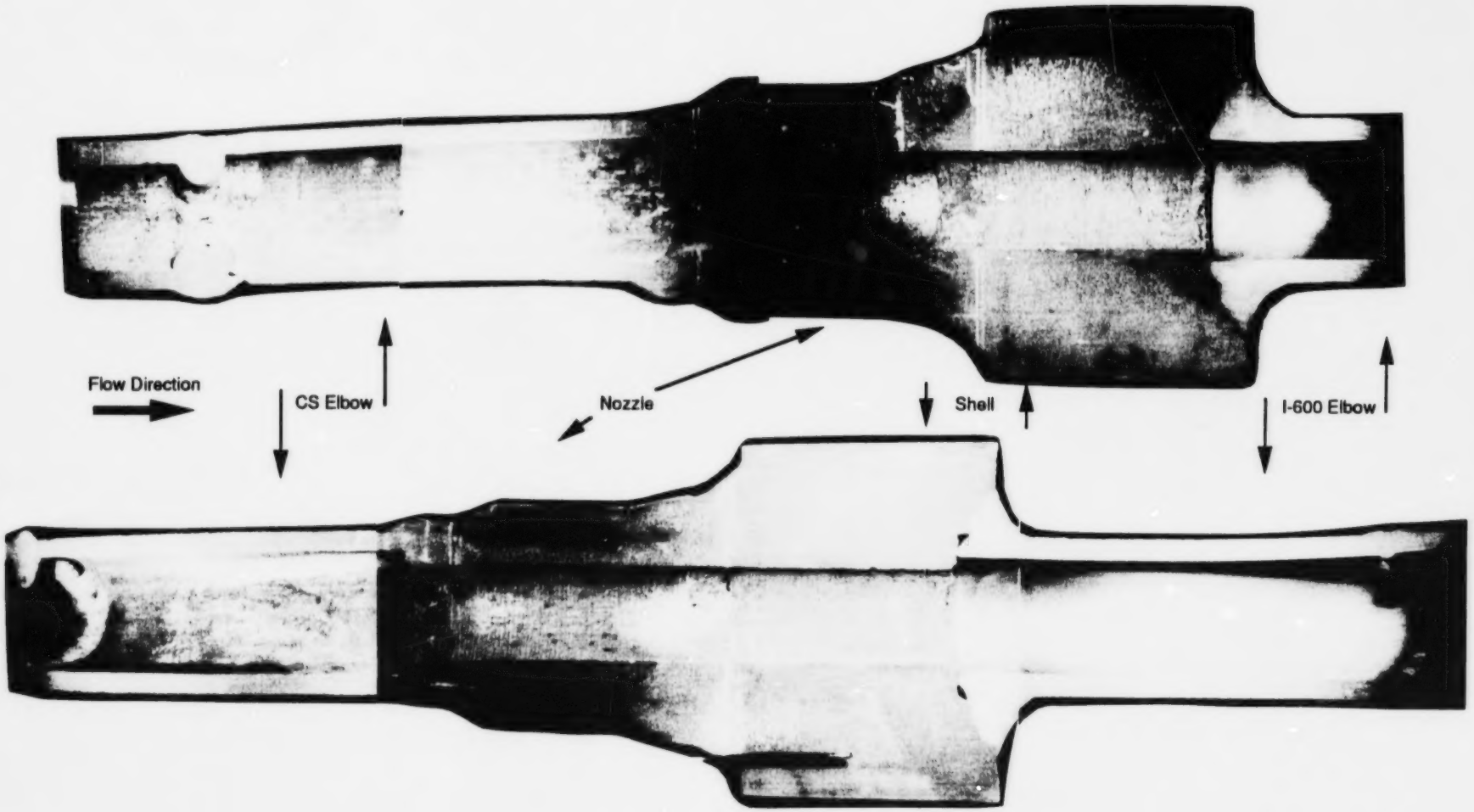


FIGURE 13
EROSION - CORROSION TEST COUPON #3

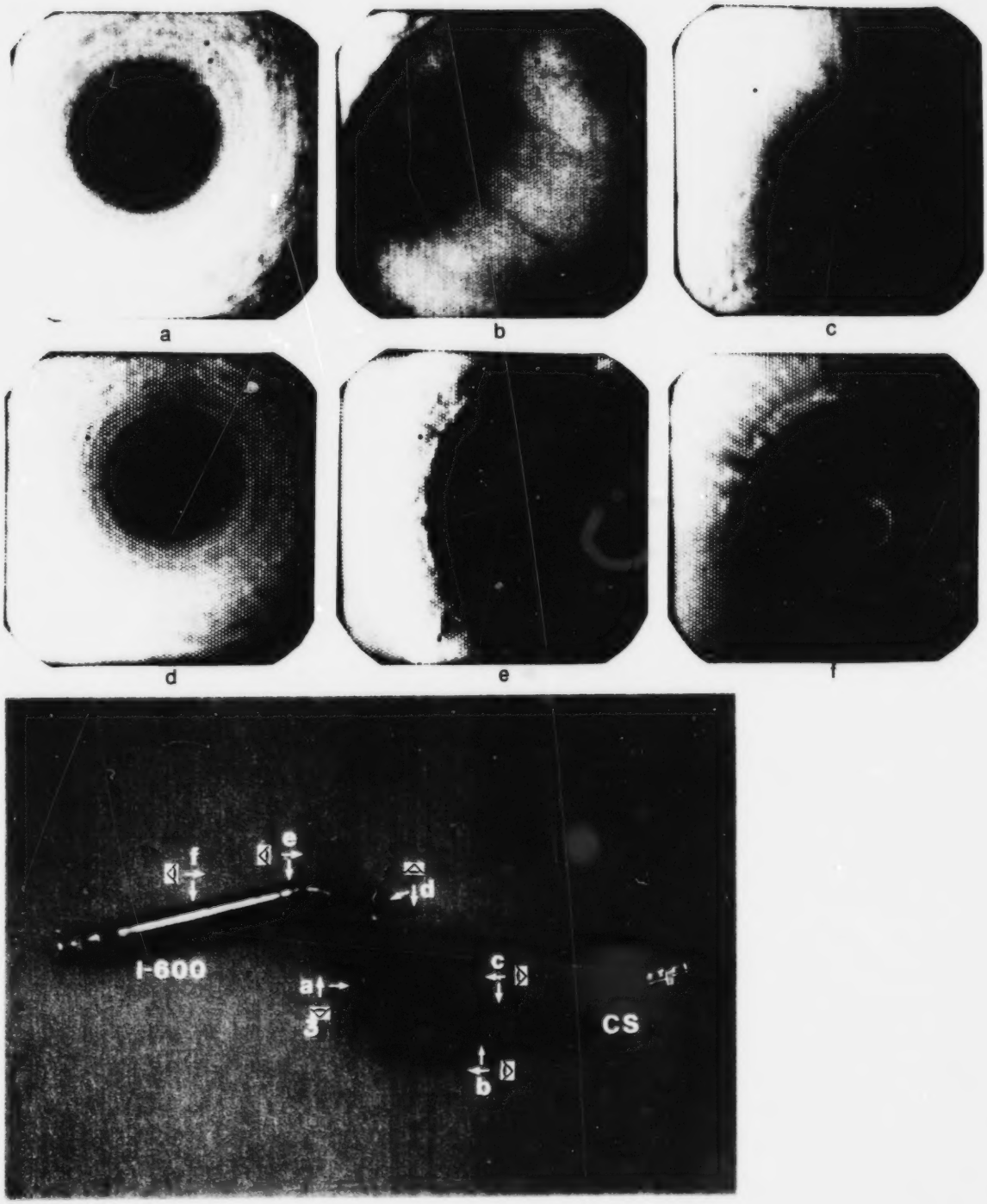
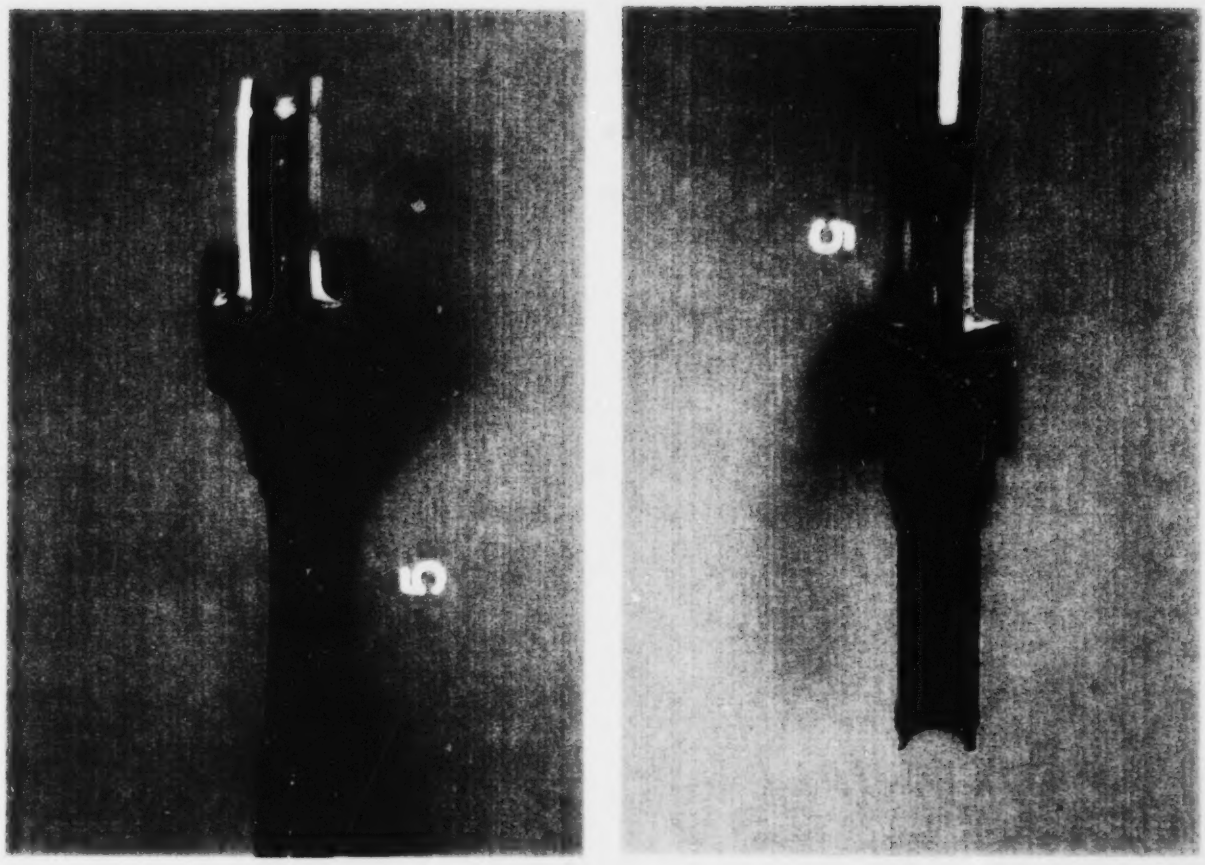


FIGURE 14
FIBRESCOPE EXAMINATION OF COUPON #3

89-133
179943-C9-RD



Test Conditions: Iron Removal Step-no Inhibitor

Flow Direction
(Coupon Orientation as Shown in above Photographs)

FIGURE 15
EROSION - CORROSION TEST COUPON #5

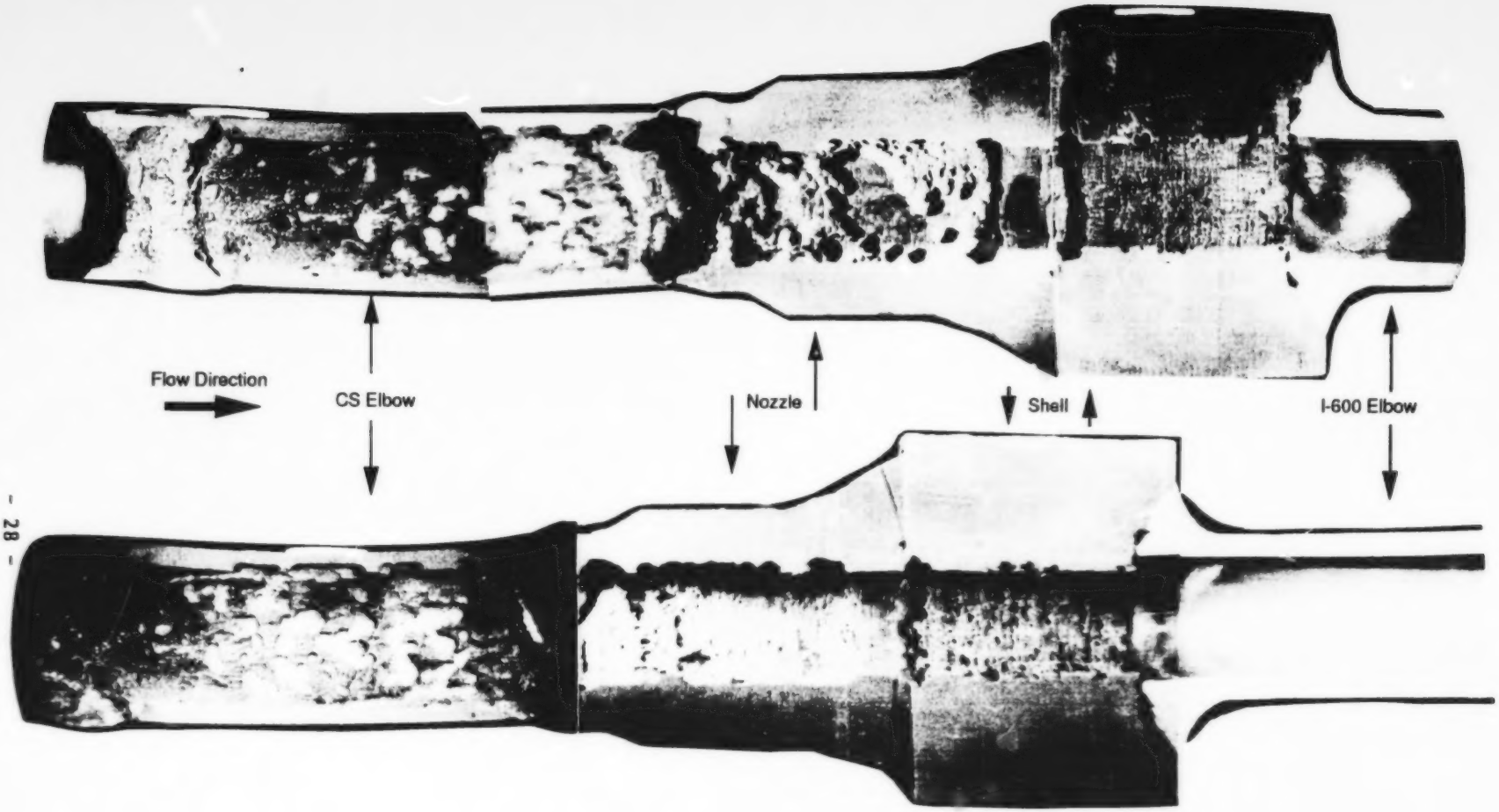


FIGURE 16
EROSION - CORROSION TEST COUPON #5

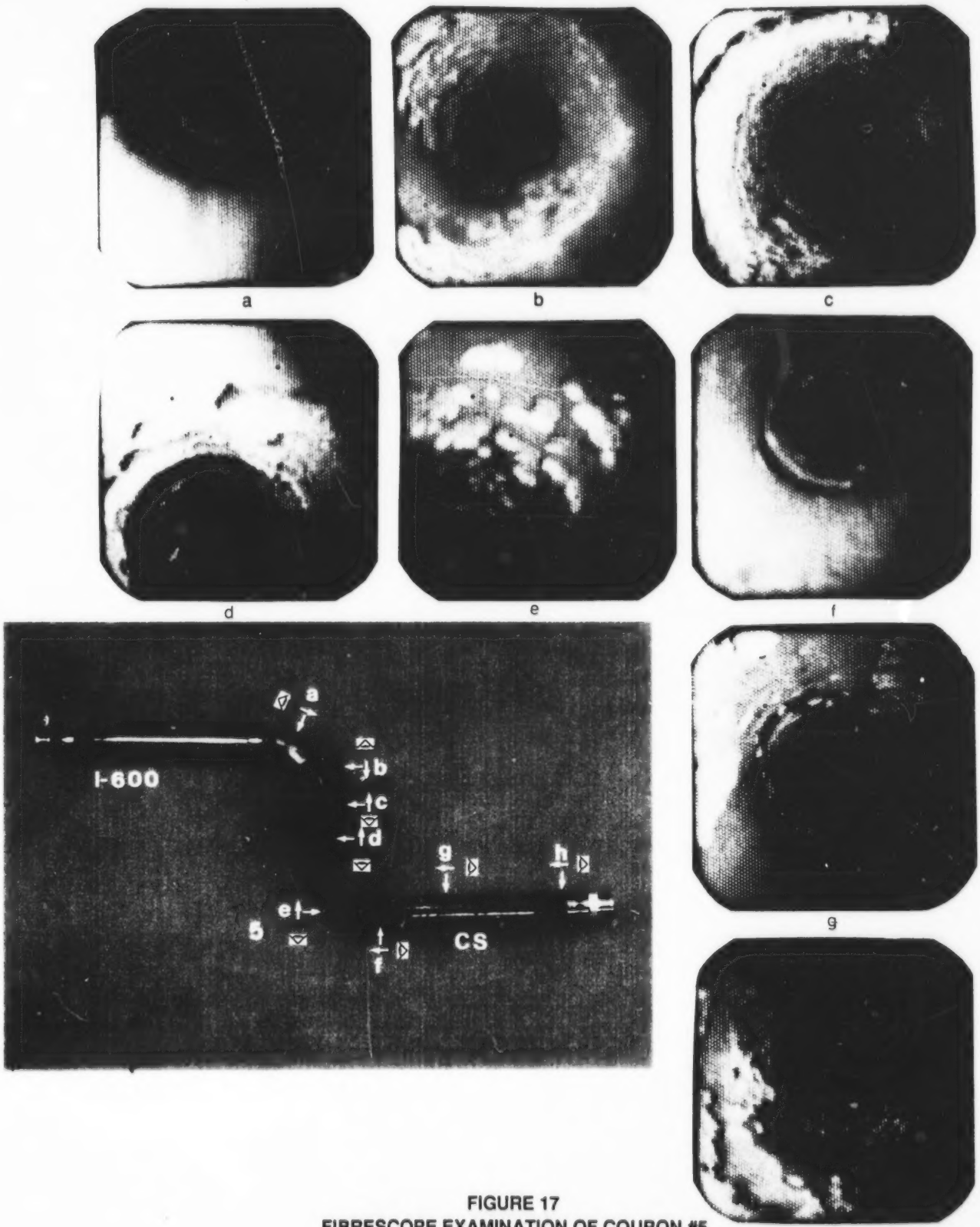
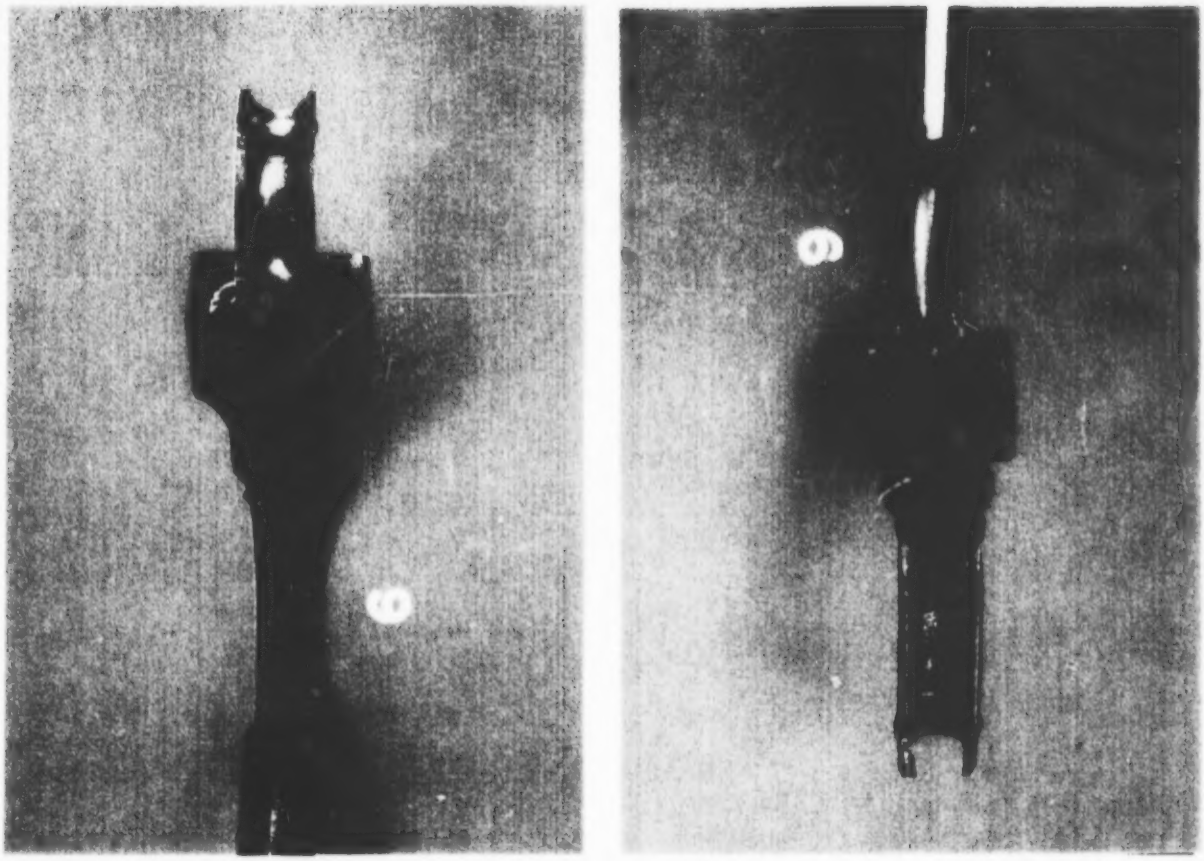


FIGURE 17
FIBRESCOPE EXAMINATION OF COUPON #5

89-133
179946-C8-RD



Test Conditions : Iron - Removal Step - no Inhibitor

Flow Direction
(Coupon Orientation as Shown in above Photographs)

FIGURE 18
EROSION - CORROSION TEST COUPON #6

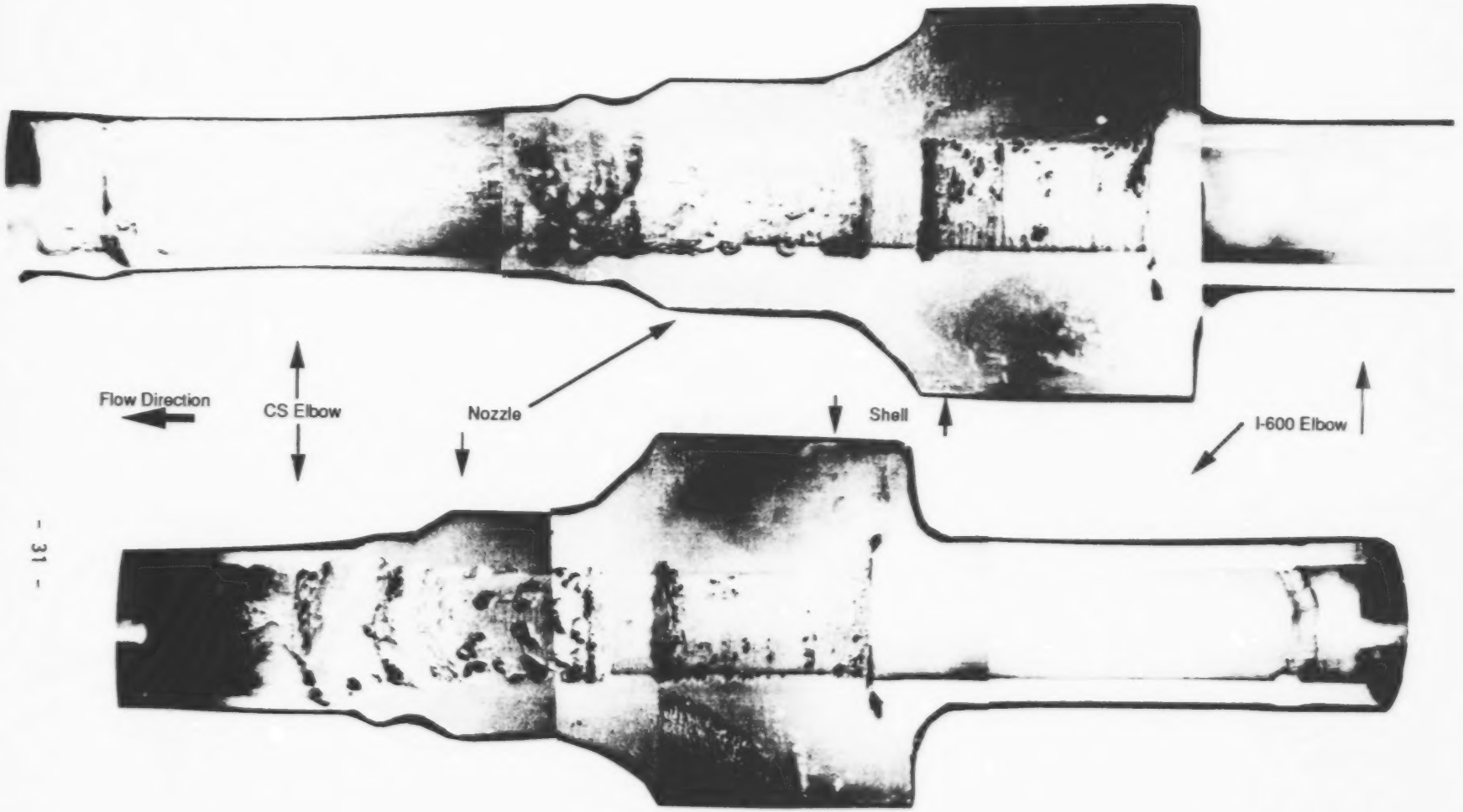


FIGURE 19
EROSION - CORROSION TEST COUPON #6

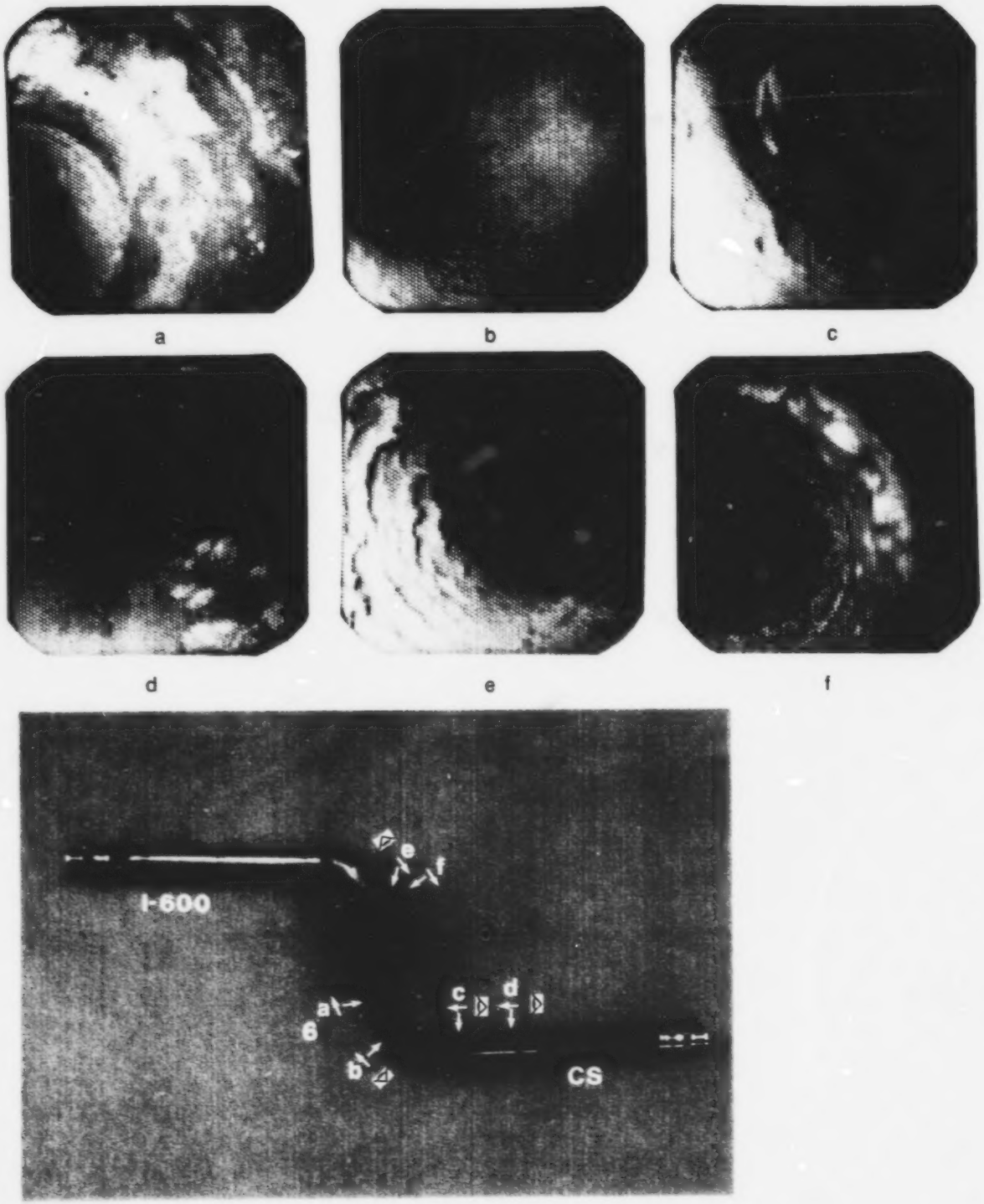
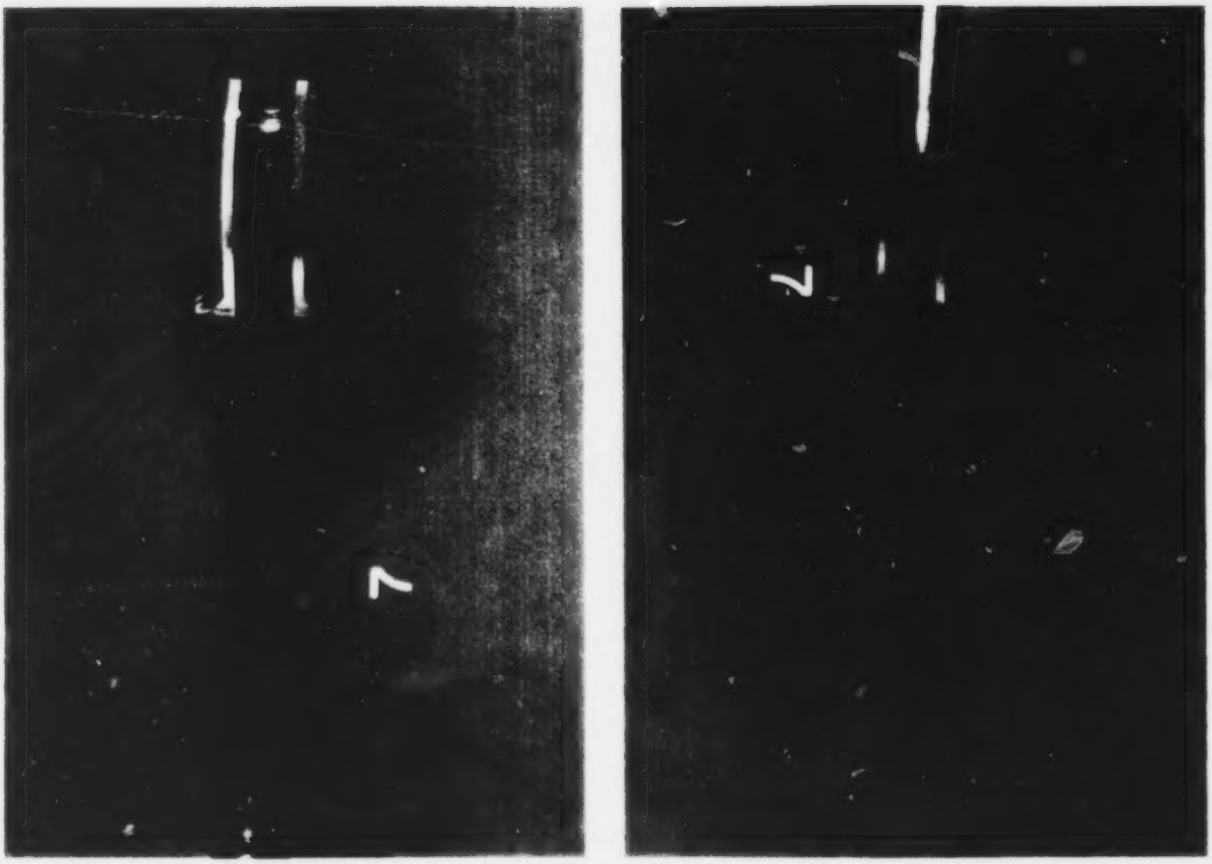


FIGURE 20
FIBRESCOPE EXAMINATION OF COUPON #6

89-133
179949-C8-RD



Test Conditions: Iron Removal Step Containing 1% CCI-801 Inhibitor

Flow Direction
(Coupon Orientation as Shown in above Photographs)

FIGURE 21
EROSION - CORROSION TEST COUPON #7

89-133
179950-C8-RD

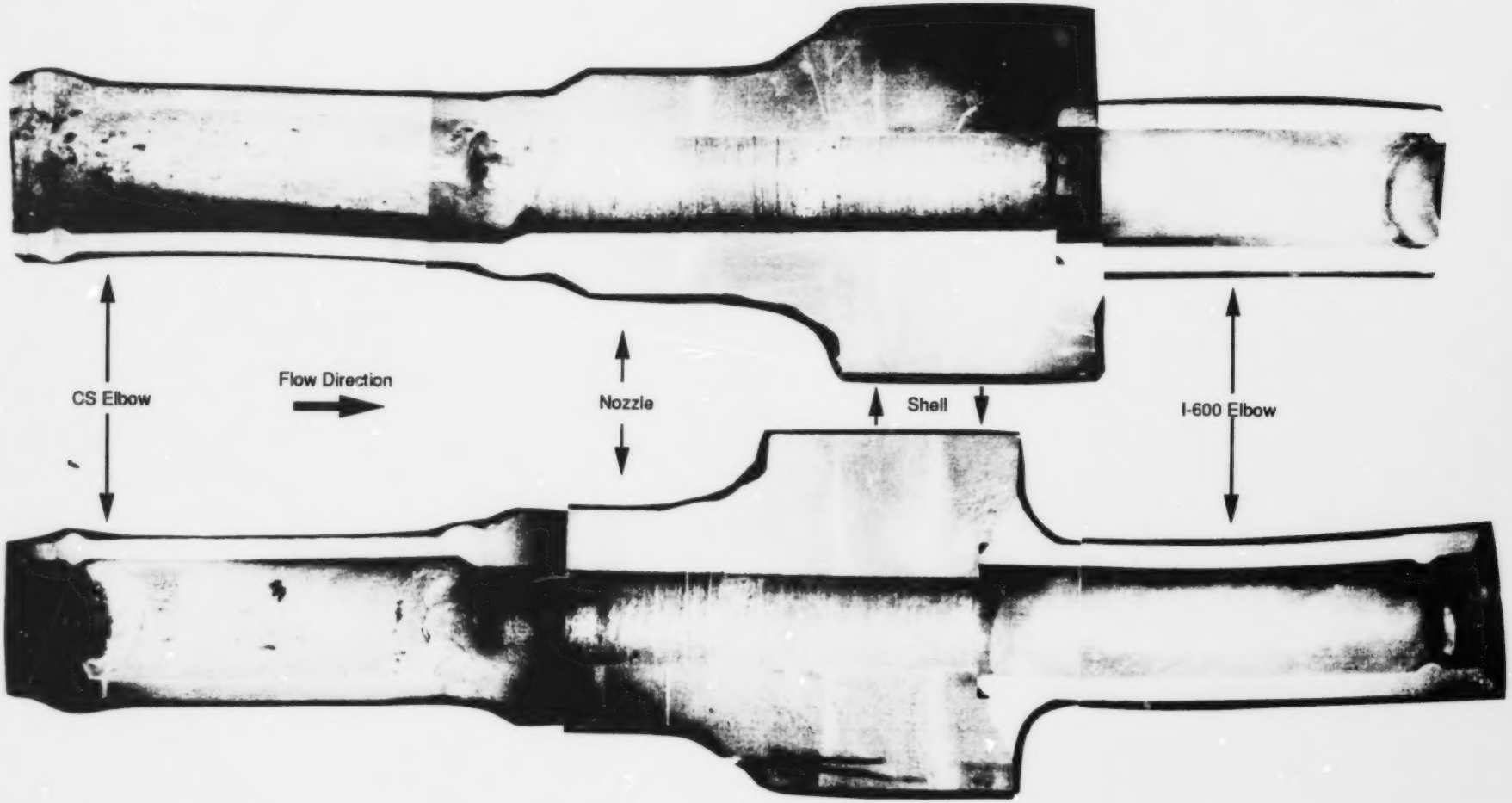


FIGURE 22
EROSION - CORROSION TEST COUPON #7

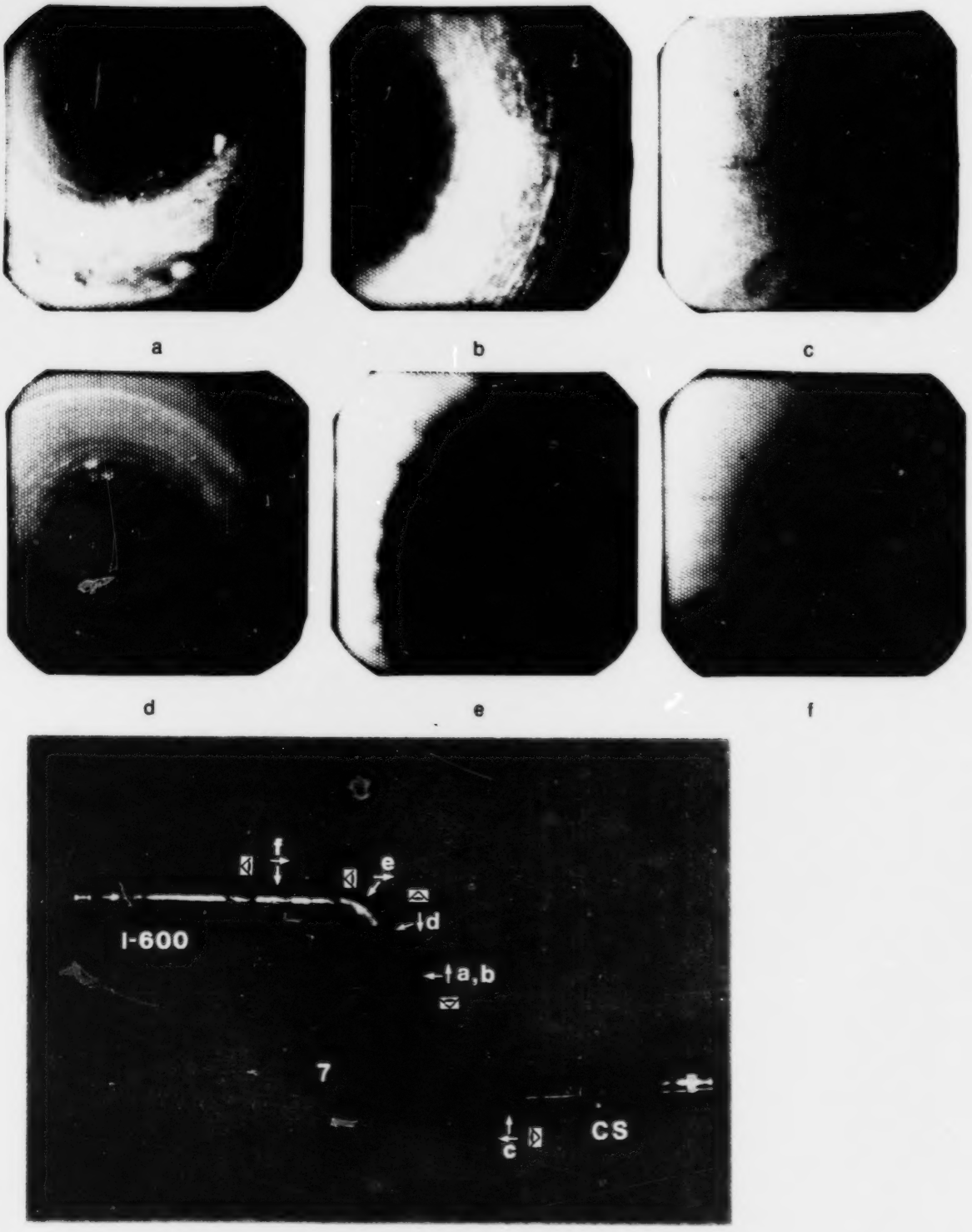
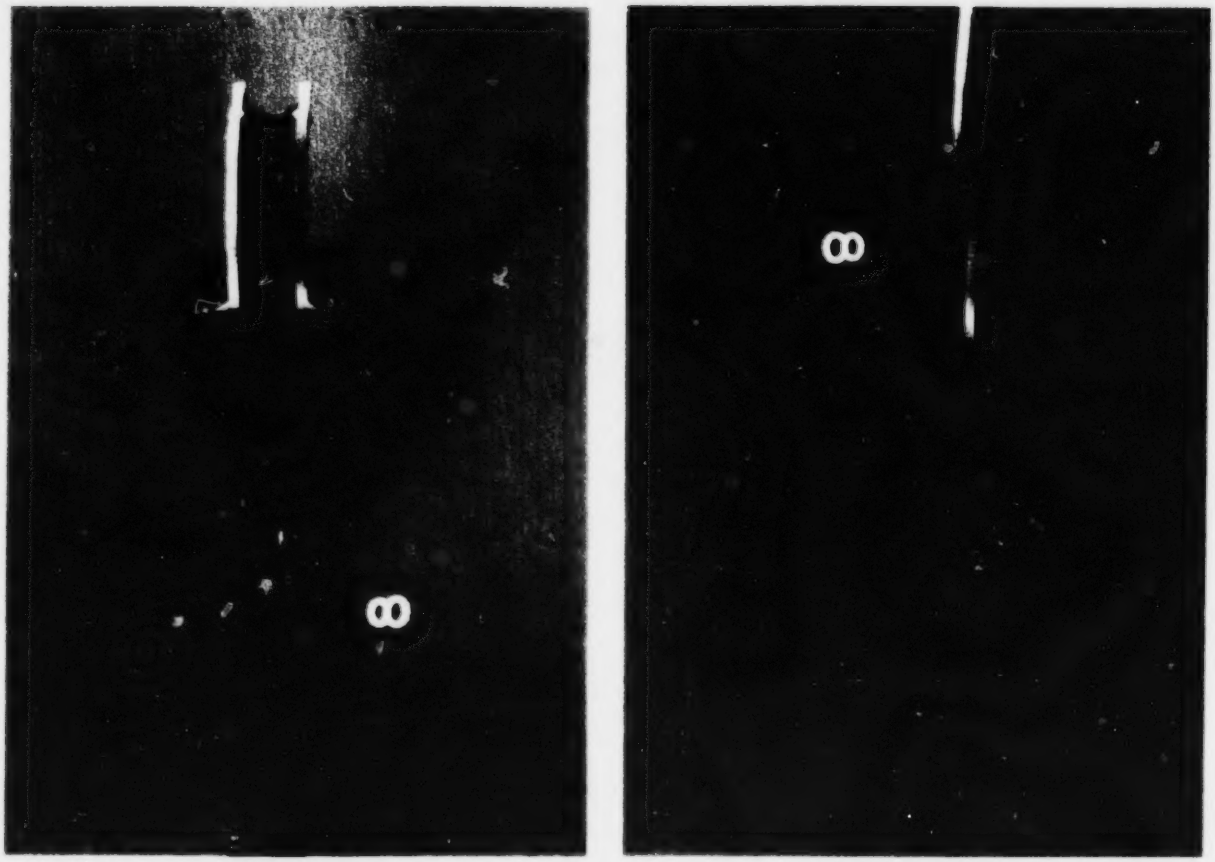


FIGURE 23
FIBRESCOPE EXAMINATION OF COUPON #7



Test Conditions: Iron RemovalStep Containing 1% CCI-801 Inhibitor

Flow Direction
(Coupon Orientation as Shown in above Photographs)

FIGURE 24
EROSION - CORROSION TEST COUPON #8

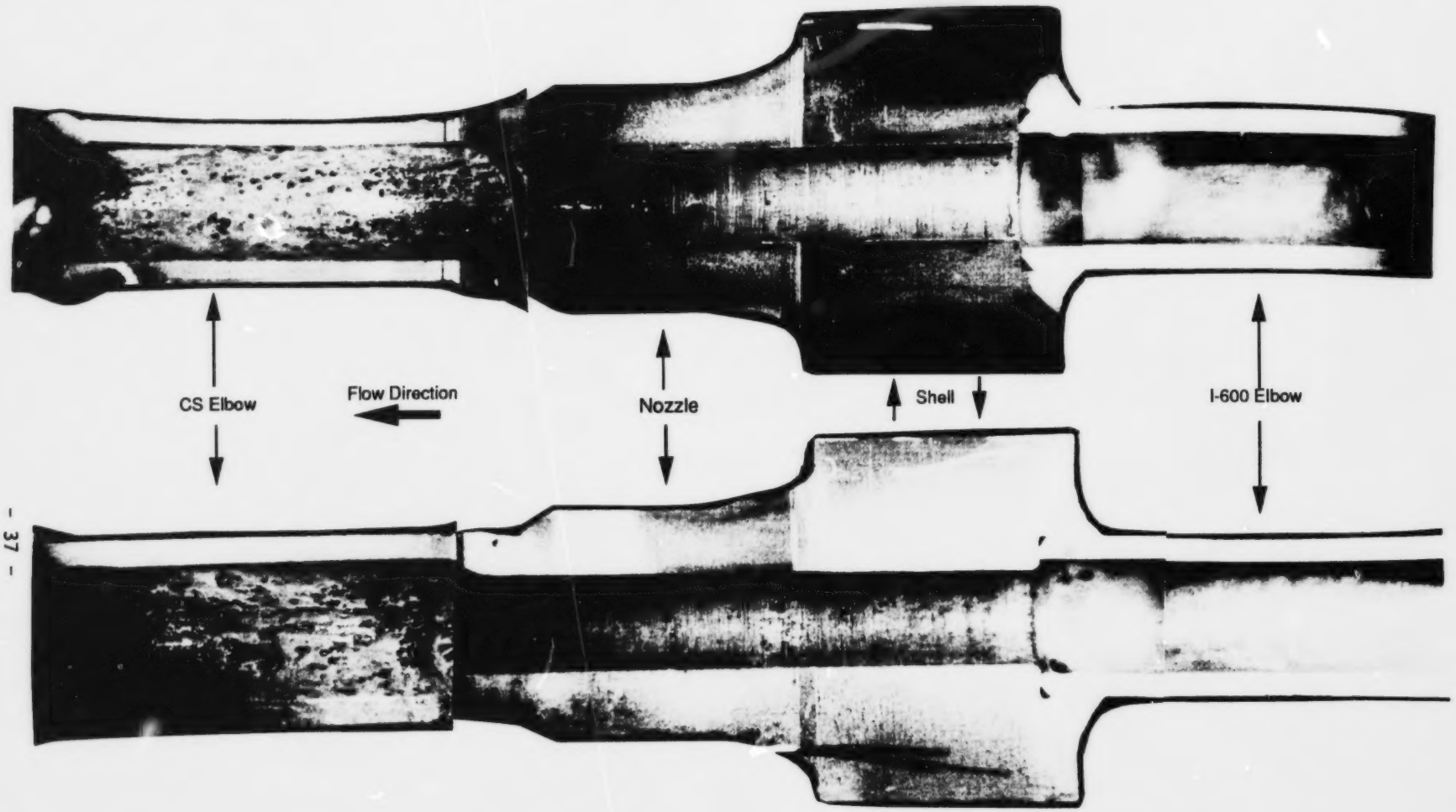
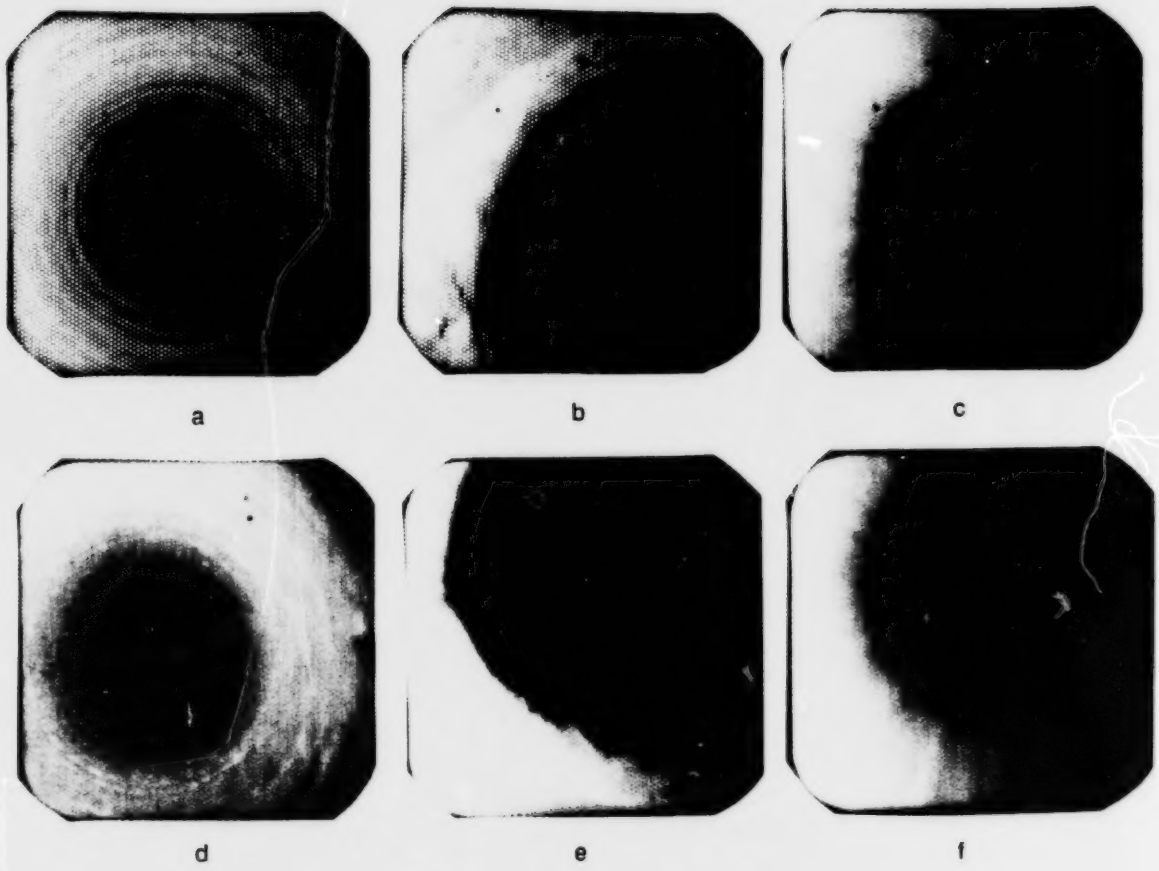


FIGURE 25
EROSION - CORROSION TEST COUPON #8



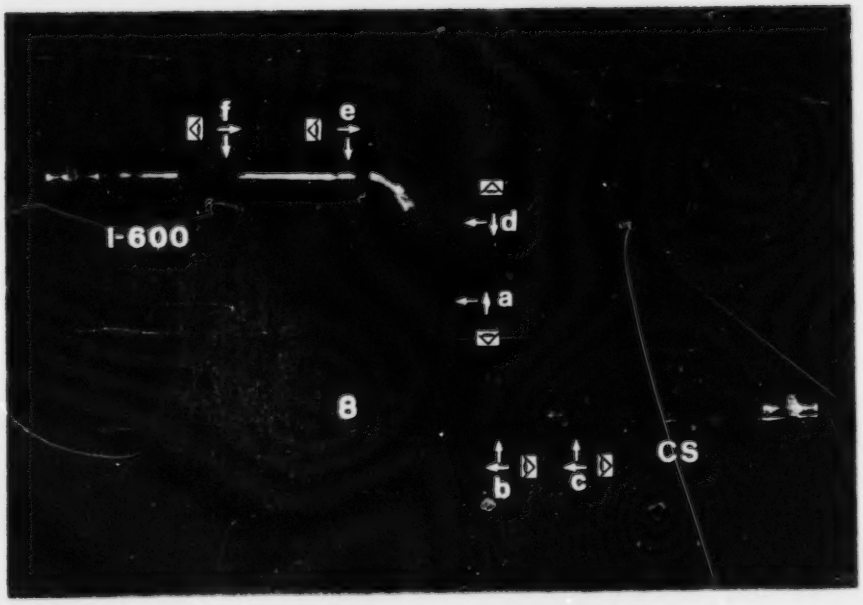
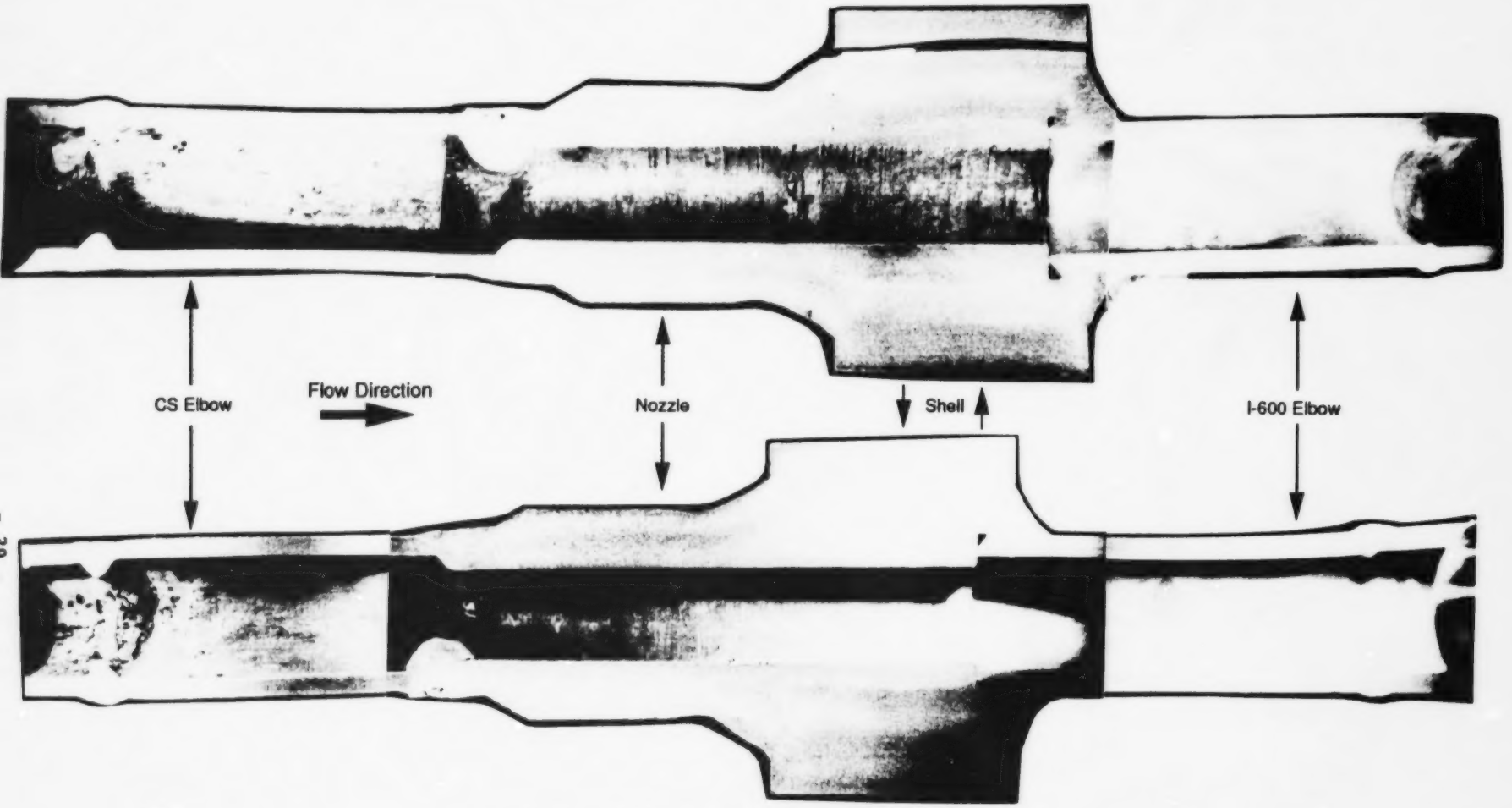


FIGURE 26
FIBRESCOPE EXAMINATION OF COUPON #8



Test Conditions: Iron Removal Step Containing 0.5% CCI-801 Inhibitor

FIGURE 27
EROSION - CORROSION TEST COUPON #9

89-133
179956-C9-RD

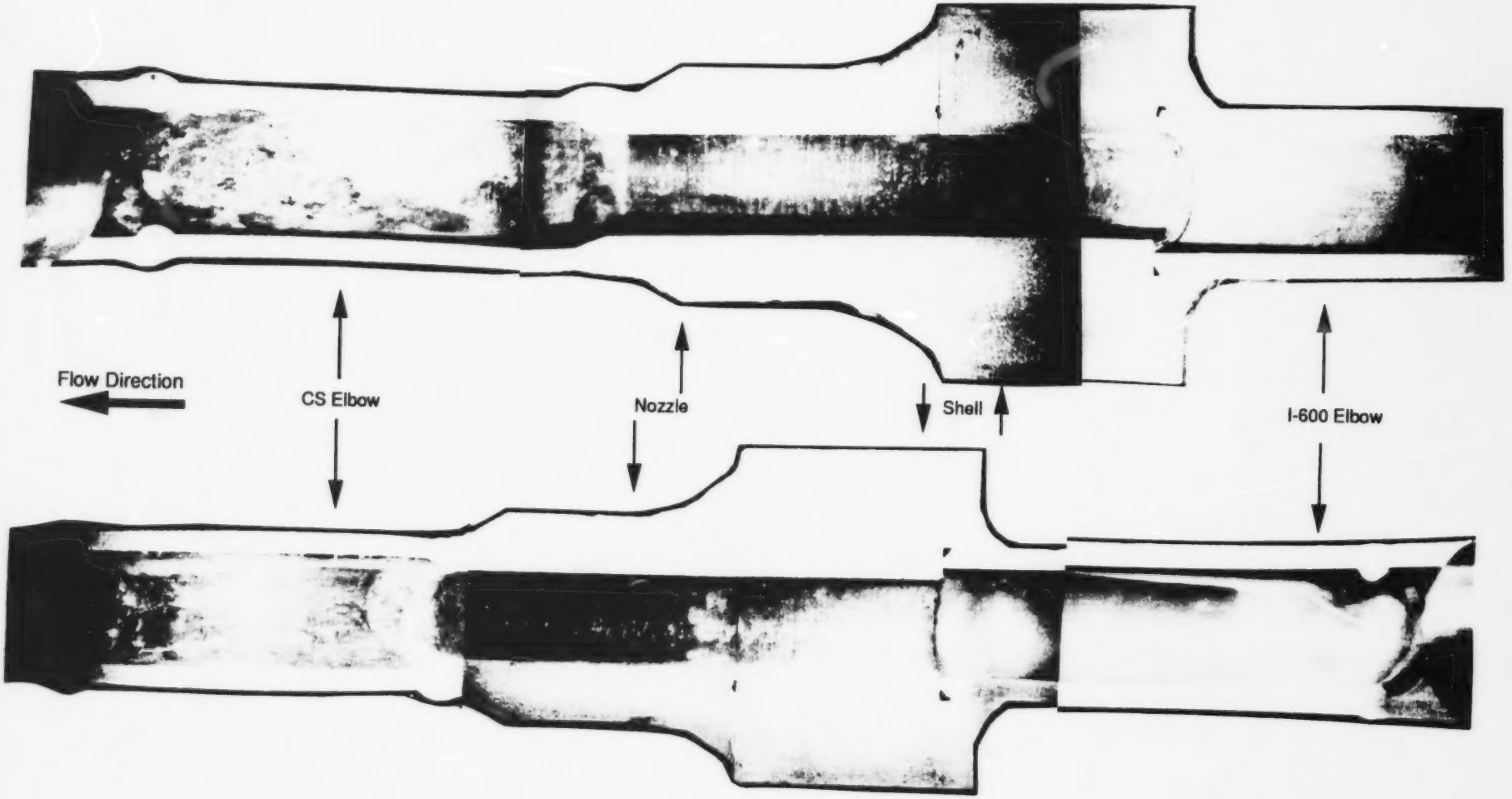
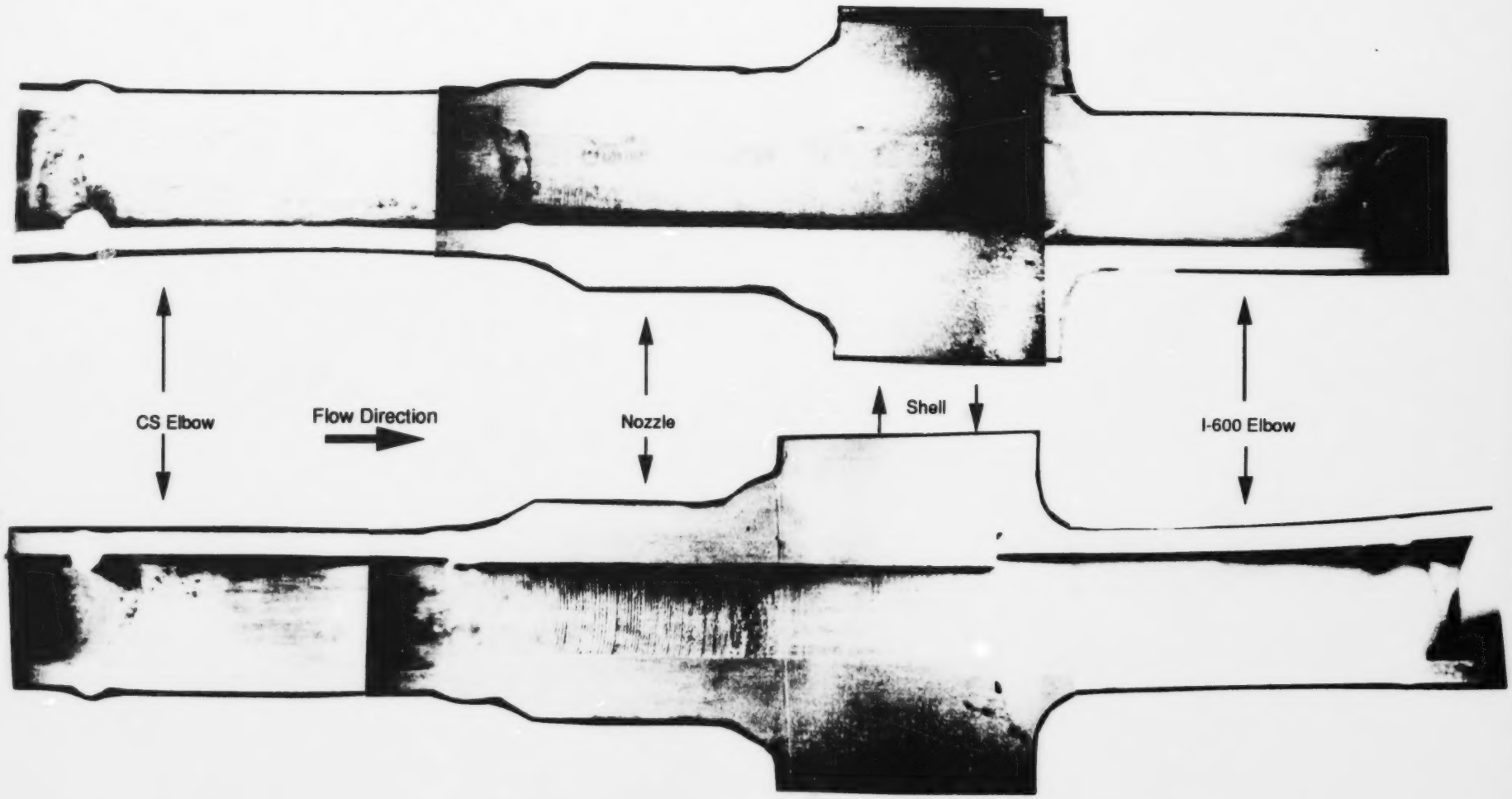


FIGURE 28

EROSION - CORROSION TEST COUPON #10
TEST CONDITONS: IRON REMOVAL STEP CONTAINING 0.5% CCI-801 INHIBITOR

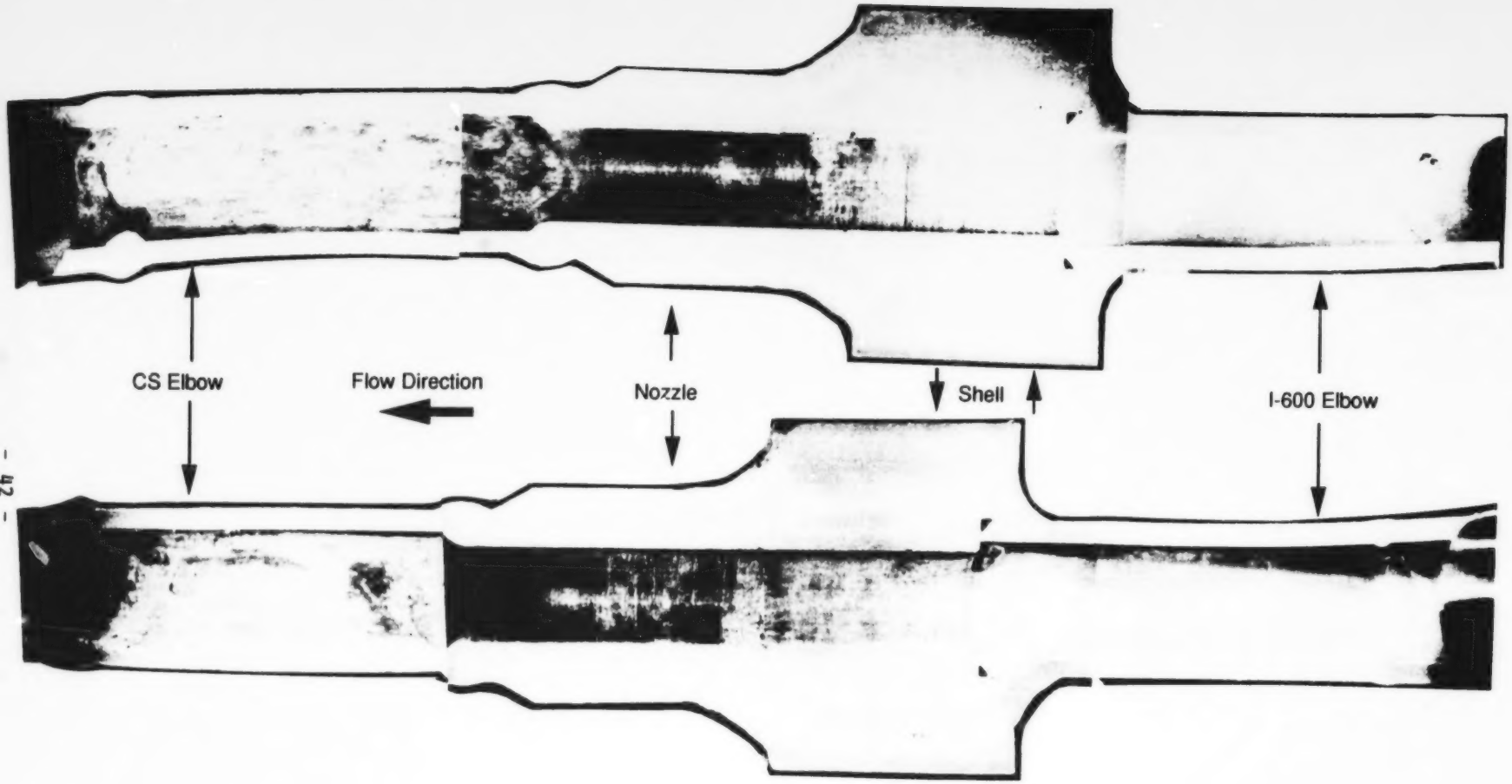
89-133
179957-C8-RD



Test Conditions: Iron Removal Step Containing 0.25% CCI-801 Inhibitor

FIGURE 29
EROSION - CORROSION TEST COUPON #11

89-133
179958-C8-RD



Test Conditions: Iron Removal Step Containing 0.25% CCI-801 Inhibitor

FIGURE 30
EROSION - CORROSION TEST COUPON #12